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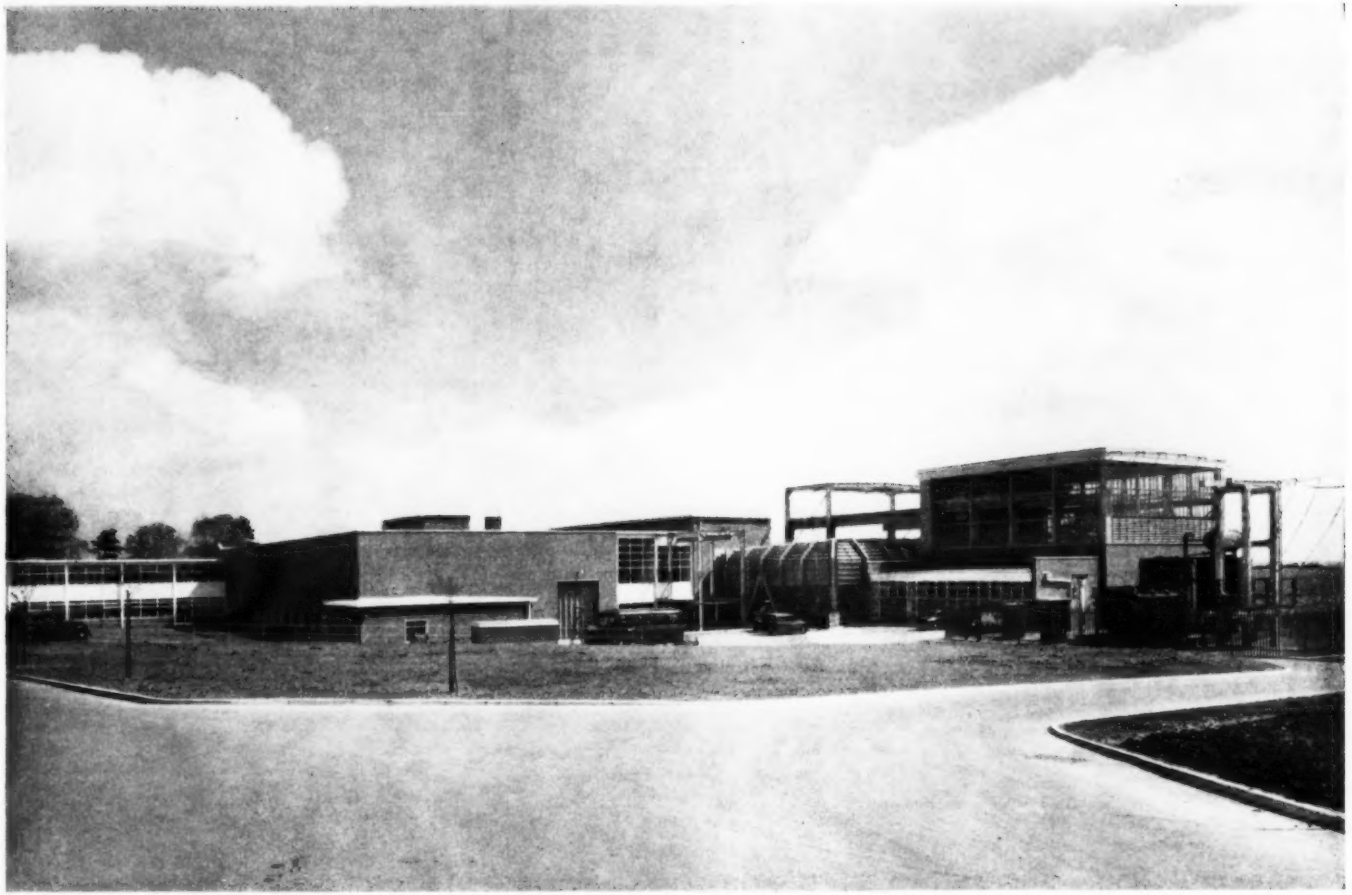


The transonic wind tunnel of the Aircraft Research Association Limited at Bedford, with associated buildings including the motor room on right

Electrical Equipment for Transonic Wind Tunnel

By P. W. R. GATLIFF, B.Sc.(Eng.), A.M.I.E.E., Chief Machine Control Engineer, and G. H. A. GUNNELL, A.M.I.E.E., Special Engineering Section.

THE TRANSONIC WIND TUNNEL of the Aircraft Research Association Limited at Bedford presented the major problem of controlling the speed of a 25,000 h.p. fan drive over wide limits to a high degree of accuracy, and this article describes the methods adopted for its solution.

Another important feature is the very large compressor required in connection with the use of perforated walls in the working section, and the drive for this is provided by a 13,750 h.p. motor.

The English Electric Company was the main contractor for the fan drive, and supplied the fan motors and compressor motor, together with their control gear and control boards, the 11 kV and 415 volt switchgear, auxiliary transformer and 415 volt motors. An 'English Electric' 30 MVA 132/11 kV transformer with on-load tap changing gear supplies the installation with power from the Grid.

The Tunnel

The tunnel is the most up-to-date of its kind in the world, with a Mach number range of 0·6 to 1·3 which enables models to be tested right through the speed of sound. In a normal wind tunnel with closed walls, model tests are not possible in a speed range from about 0·9 to 1·2 times the speed of sound, due to the constraining effect of the solid walls altering the air flow around the model. It is possible however to test models through the transonic region by perforating or slotting the tunnel walls, allowing the air to flow out through the walls in the region of the model. Perforated walls are used for the A.R.A. tunnel, and the working section is 9 ft wide × 8 ft high, enabling models of about 3 ft span to be tested.

The main tunnel circuit is of the closed type, the fan consisting of two stages, each 21 ft in diameter. A long cardan shaft taken through the tunnel wall connects the fan with the A.C. driving motor.

Complete models are held in the working section on stings from behind (Fig. 1). This method of support produces minimum air-flow disturbance around the model. The sting is pivoted on a vertical strut carried on a model cart which can be run in or out of the tunnel on rails. The mechanism operating the sting is so constructed that the incidence of the model may be changed while its vertical position remains approximately constant. A rolling mechanism is also incorporated in the sting, so that by rolling the model and operating the incidence control, angles of sideslip can be obtained and stability measurements made.

Initial rigging of the model on the cart is carried out in one of the five model bays adjacent to the tunnel. By using several model carts the maximum use can be made of the tunnel equipment and of operators' time.

Main Drive

The original specification called for a main fan drive motor continuously rated for 20,000 h.p. at 490 r.p.m. with an automatic speed control above 350 r.p.m. to achieve a speed holding accuracy of $\pm$ 0·2% of set speed for a short time. Several types of drive were considered and that finally adopted has fulfilled these requirements and has been operating successfully for some time.

A Ward-Leonard drive upon investigation was found too expensive in first cost, in view of the large D.C. machines involved and the size of the

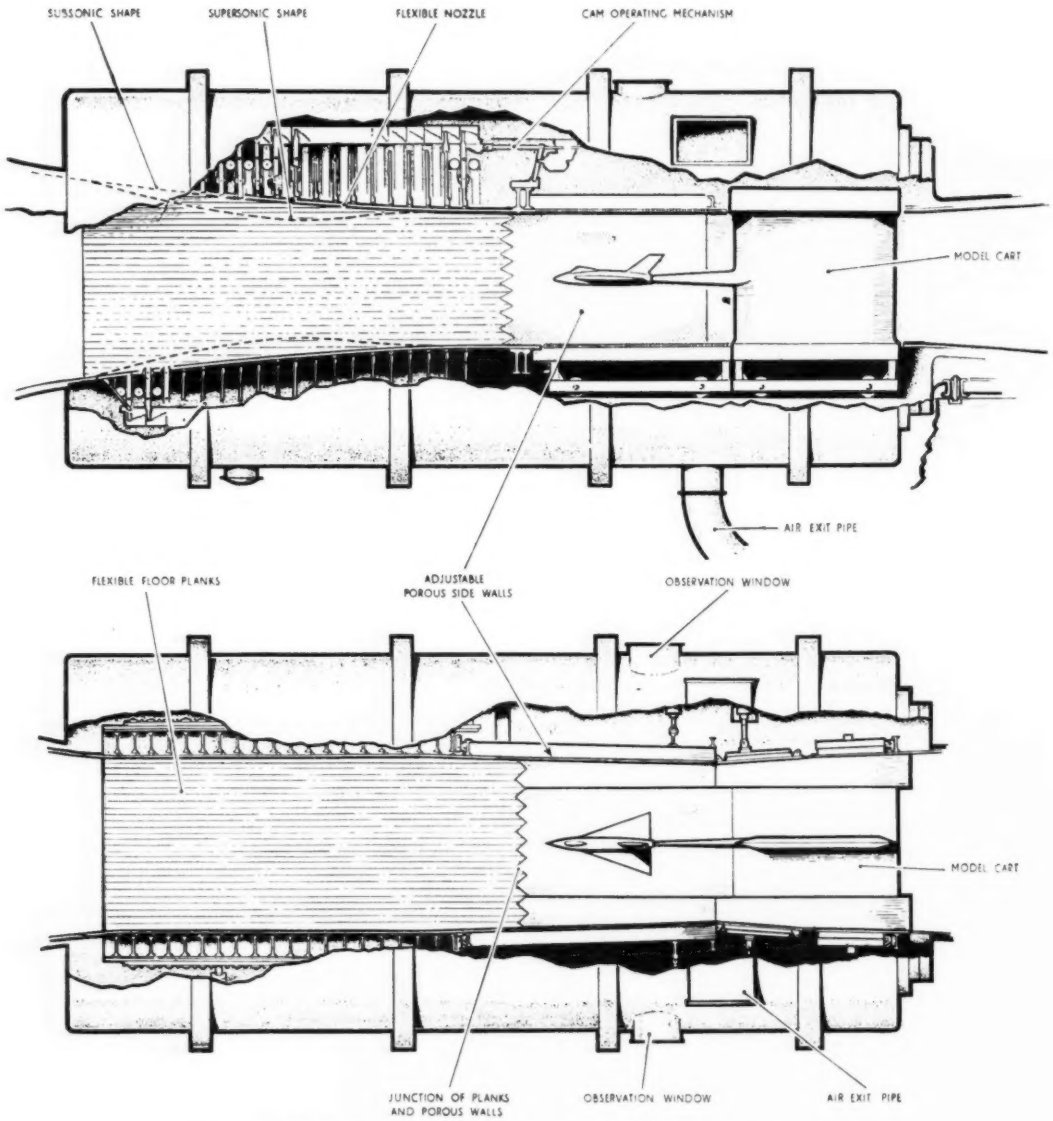


Fig. 1.—The working section, with model held on sting from model cart

motor-generator set necessary to give maximum power at top fan speed. Also, the fixed losses of this motor-generator set, which might run continuously, were appreciable, and therefore the Ward-Leonard drive was considered uneconomic. It will be realised that the power required to drive such a fan varies as the third power of the speed, so that at 350 r.p.m. for example, it is only 35% of the maximum. The overall efficiency of the Ward-Leonard drive would therefore be poor during low-speed running and when the fan was stationary.

The cheapest drive in terms of initial cost was undoubtedly the straight A.C. induction motor,

with speed variation by rotor resistance control. Here again the efficiency is low at reduced speeds, but the fixed losses are nil when the fan is stationary. Although the A.C. motor would have been cheaper to install and operate than the Ward-Leonard drive, it was rejected for the following reasons. The induction motor speed is controlled by the value of rotor circuit resistance, and the ratio of change in speed to change in rotor resistance is very much a variable for a fan load. This ratio is effectively the 'gain' of the motor in a closed-loop control, and hence any such control is non-linear. Also it was considered that the high negative temperature coefficient of resistance of the electrolyte used in the liquid controller would tend to cause instability in such a system. Other objections to the slipring induction motor for the main fan drive were the prolonged starting current, and the bad power factor particularly at the lower speeds.

The third type of drive considered was a modified Kramer system, utilising the slip energy of an induction motor and converting it into D.C. power by means of a motor-generator set. The Kramer system is attractive for starting and speed control but it is expensive because of the low speed at which one of the motor-generator sets has to run at the higher fan speeds. Power factor correction can be effected over the whole speed range.

It was felt that many of the advantages of the Kramer control could be obtained with a D.C. motor mechanically coupled to the main A.C. fan motor and supplied at variable voltage by a motor-generator set as in a Ward-Leonard drive. This composite drive was adopted, employing a 1,500 h.p. (2-hour rating) D.C. motor coupled to a 25,000 h.p. (2-hour rating) slipring induction motor (Fig. 2).

Fig. 3 shows the arrangement of the plant in diagrammatic form, and Fig. 4 the principal elements in the control system.

A.C. Motor

The supply to the A.C. motor is at 11,000 volts 3-phase 50 cycles, and the full load stator current based on 20,000 h.p. continuous rating is 950 amp.

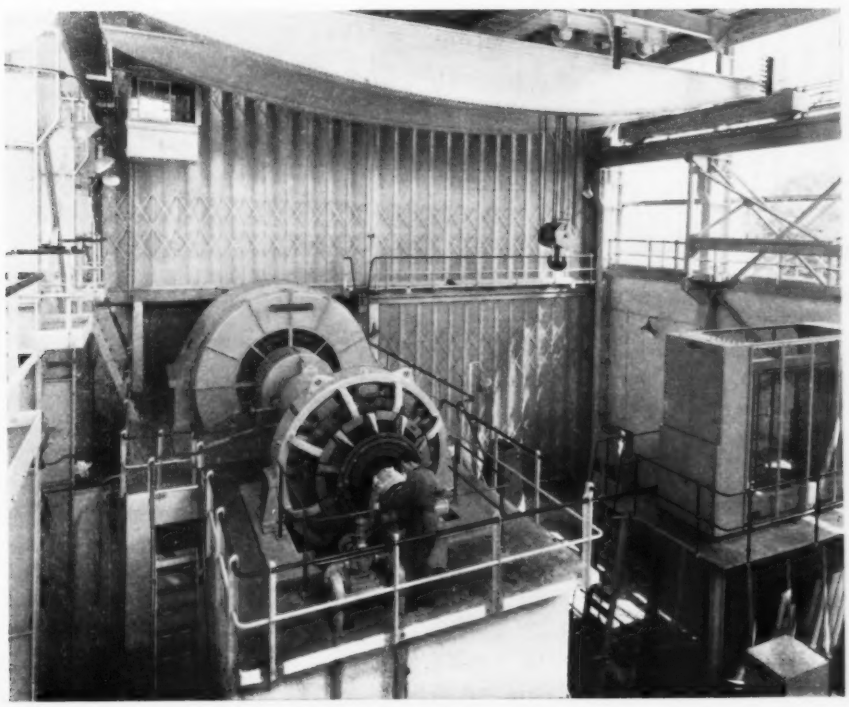


Fig. 2. The 25,000 h.p. induction motor and 1,500 h.p D.C. motor driving the main fan

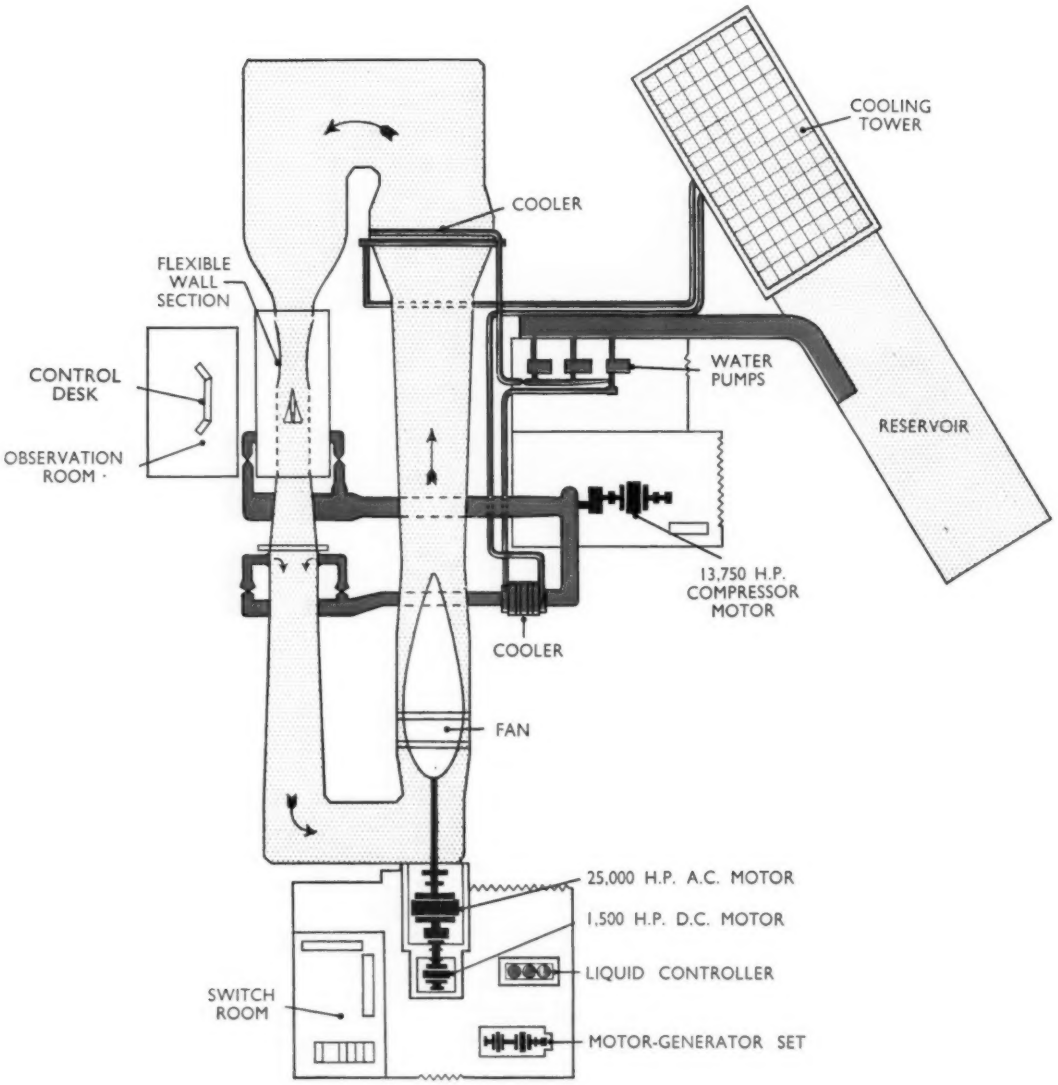


Fig. 3.—Diagrammatic arrangement of plant

The motor shaft and coupling are so designed that at a future date it will be possible to add a further 25,000 h.p. motor to drive through the shaft of the existing motor, so that a total of 50,000 h.p. will then be available.

In view of the large amount of electrical power involved in starting and running such a motor from the 132 kV grid system, the Central Electricity Authority stipulated a rate of growth of load not exceeding 7,000 kW per minute.

The motor is self ventilated by air drawn in from the motor room ; the warmed air is ducted outside the building. The sliprings and brush-gear are mounted internally, i.e. inside the bearing

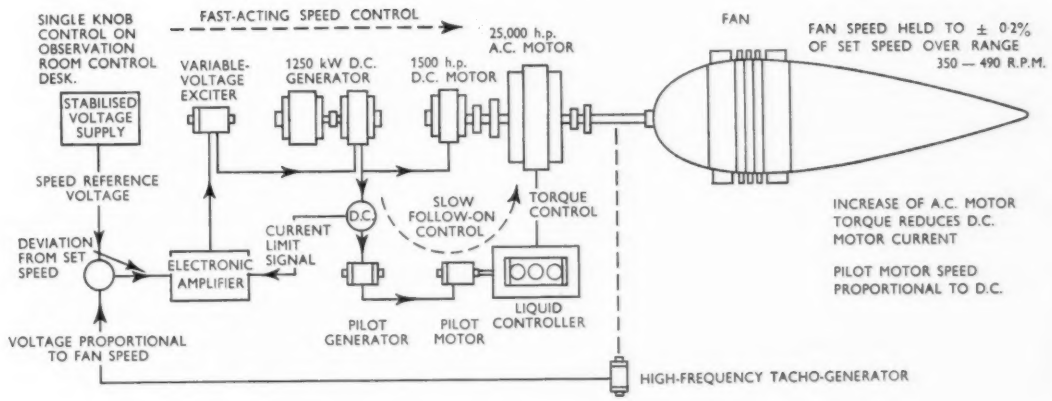

SINGLE KNOB CONTROL ON OBSERVATION ROOM CONTROL DESK.
FAST-ACTING SPEED CONTROL
25,000 h.p. A.C. MOTOR
FAN
FAN SPEED HELD TO ± 0·2% OF SET SPEED OVER RANGE 350 — 490 R.P.M.
VARIABLE-VOLTAGE EXCITER
1250 kW D.C. GENERATOR
1500 h.p. D.C. MOTOR
STABILISED VOLTAGE SUPPLY
SPEED REFERENCE VOLTAGE
SLOW FOLLOW-ON CONTROL
TORQUE CONTROL
INCREASE OF A.C. MOTOR TORQUE REDUCES D.C. MOTOR CURRENT
PILOT MOTOR SPEED PROPORTIONAL TO D.C.
CURRENT LIMIT SIGNAL
DEVIATION FROM SET SPEED
ELECTRONIC AMPLIFIER
LIQUID CONTROLLER
PILOT GENERATOR
PILOT MOTOR
VOLTAGE PROPORTIONAL TO FAN SPEED
HIGH-FREQUENCY TACHO-GENERATOR

Fig. 4.—Principal elements in control system

span. The motor bearings are of the self aligning type, split horizontally, and are lubricated and cooled by a continuous oil supply under pressure, the oil being forced through an oil cooler and afterwards passed through the bearings and drained into an oil reservoir from which the oil pump draws its supply through strainers. The main oil pump is mechanically driven through a gear-box from the main shaft. In addition, a motor-driven standby oil pump is automatically started when the lubricating oil pressure falls below a predetermined value. To reduce the friction and wear of the main bearings during starting, a high pressure jacking oil pump is provided.

Normally the motor is stopped by tripping the main oil circuit-breaker, whereupon the shaft speed decreases under the action of the fan load torque assisted by regenerative braking on the D.C. motor. However, a main shaft holding brake is provided which may be operated manually at speeds below 50 r.p.m. to assist stopping, if necessary.

D.C. Motor

The D.C. motor is rated at 1,200 h.p. continuously and at 1,500 h.p. for two hours. The armature voltage is 520 volts and the motor is supplied from a 1,250 kW generator driven by a synchronous motor. Full-load current is 1,840 amp and the base speed 250 r.p.m.

The motor is however capable of delivering constant horse-power over a field weakening range from 250 r.p.m. to 500 r.p.m. The field system is separately excited from a constant voltage source and the pole faces are wound with a series-connected winding to compensate for the effects of armature reaction over the entire load range. The motor is forced ventilated from a fan mounted underneath the bedplate, the cooling air blowing out over the commutator.

The D.C. motor is capable of relatively large torques at low speed, and hence is suited to starting the fan from rest. The A.C. motor is normally switched in when the fan speed reaches approximately 200 r.p.m.

Liquid Controller

Control of the fan speed is obtained by adjustment of a liquid resistance connected in the rotor circuit of the induction motor. The liquid controller (Fig. 5), which has a continuous dissipating capacity of 3,500 h.p., is of the new BL type developed by The English Electric Company for use with large A.C. motors, and has the following features :—

(1) Three separate cell assemblies, one for each phase, electrically insulated from each other.
(2) Forced electrolyte circulation, the cooled electrolyte being pumped into the bottom of each cell.
(3) A simplified operating mechanism.
(4) A Ward-Leonard fed pilot motor to give rapid and accurate control.
(5) Simplified electrode construction.

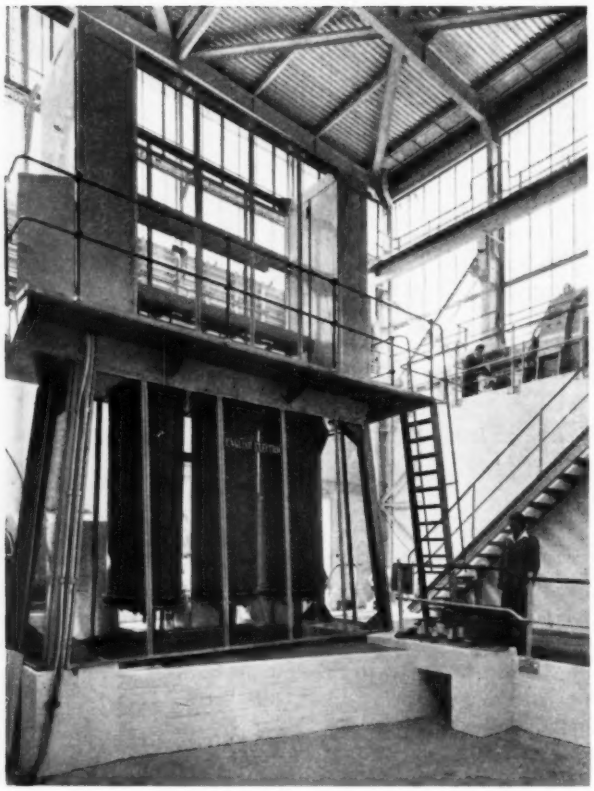


Fig. 5.—The liquid controller for the 25,000 h.p. main fan drive motor

The circulating pump forces the electrolyte through a heat exchanger into a header tank at the top of the rheostat and from there down three stand pipes to the areas below the fixed electrode. Holes are provided in this electrode through which the electrolyte can flow upwards in the cell. Subsequently it passes through corresponding holes in the moving electrode and then to the top of the cell where it flows over a weir and returns to the sump. A heat exchanger of standard design is used to transfer the heat from the electrolyte into cooling water. As the resistance decreases considerably with increasing temperature, the cooling-water flow is thermostatically controlled to keep the electrolyte entering the controller at a nearly constant temperature, independent of the heat energy to be dissipated.

The operating mechanism consists of a D.C. pilot motor driving the electrode shaft through a worm gear and heavy chains at each end of the controller. A counter weight is provided to balance the moving system so that approximately equal pilot-motor torques are required for raising and lowering. Adjustment of the electrode speed can readily be made by choice of sprocket wheels and chain drive. The pilot motor is energised from a pilot generator, the output voltage of which is proportional to the direct-current flowing in the main Ward-Leonard loop. A separate field is provided on this generator for manual operation of the liquid controller.

Attached to the operating chain is an arm that actuates cam-type limit switches for stopping the pilot motor when the electrodes reach the extreme positions, and for other purposes such as pilot lights and interlocks : also driven from the electrode chain is a Desynn transmitter to give indication of the liquid controller position at the operating desk in the observation room.

Speed Control

The speed control scheme is of the 'regulator' kind, maintaining constant set speed over the range from 350 r.p.m. to top speed, independent of tunnel load variations, ambient temperature changes and supply voltage variations. The speed regulator acts quickly on the D.C. motor causing it to deliver positive or negative correcting torque within its capacity. The liquid rheostat of the A.C. motor is controlled automatically to hold the D.C. motor load at approximately zero, so providing a slower 'follow-on' control transferring the additional torque from the D.C. motor to the A.C. motor. Thus, the liquid rheostat comes to rest only when the D.C. motor torque has fallen to near zero and the speed corresponds to the set speed. In this way, the full torque of the D.C. motor is available to correct for any disturbance to the system.

The fan speed is detected by a high-frequency inductor type alternator, the output voltage of which is rectified and smoothed. The resulting

D.C. voltage is proportional to shaft speed. The speed reference voltage is obtained from a stabilised electronic source fed across a high stability resistance. To obtain the necessary sensitivity of setting, a 40-turn helical potentiometer is used, mounted on the observation room control desk (Fig. 6). The difference voltage between input and output, or 'error' signal, is fed into an electronic amplifier. The action of the amplifier and of the tacho-generator and speed reference supply has been described in connection with another installation in a previous number of this Journal.*

Referring to the circuit diagram in Fig. 7, the amplifier output is fed into the field winding of the generator exciter, which in turn feeds the main generator. The time lag in the electronic amplifier is negligible, being due only to an input filter circuit, and the gain of the amplifier is such that full output can be obtained with only a few volts change in the input.

The D.C. motor field weakening rheostat is set manually to the maximum permissive speed ; this gives the maximum D.C. torque for the selected fan speed. To facilitate setting up, the motor field ammeter is scaled in r.p.m. Should the control inadvertently be set for a speed higher than that for the motor field setting, an overvoltage occurs on the main generator which is therefore protected by an overvoltage relay.

The ultimate response of the speed control depends upon the moment of inertia of the rotating system. This gives a mechanical time constant much larger than any of the electrical time delays in the system, but for a large error the correcting torque must be held within the capacity of the D.C. motor to allow for the inertia time lag. This limiting torque feature is achieved by using a current limit signal, derived from the voltage drop across the series windings in the main Ward-Leonard loop, to cut off the electronic amplifier in the accelerating condition. Regenerative current limit acts the opposite way to boost the amplifier output during deceleration.

During manual operation of the tunnel, when the electronic amplifier is not in use, a separate current limit circuit is in operation. A current signal obtained from the pilot exciter is backed off against a reference exciter biassing voltage controlling the rate of change of generator voltage. The main loop current is fed through the field of this pilot exciter. The field windings have so few turns that the time constant is negligible. A small

* *A. P. Baines and B. W. McLaughlin. Speed control of rotating beam equipment in the Admiralty Research Laboratories at Bushy Park. E. E. Journal Vol.* 14, *No.* 5, *March* 1956, *p.* 3.

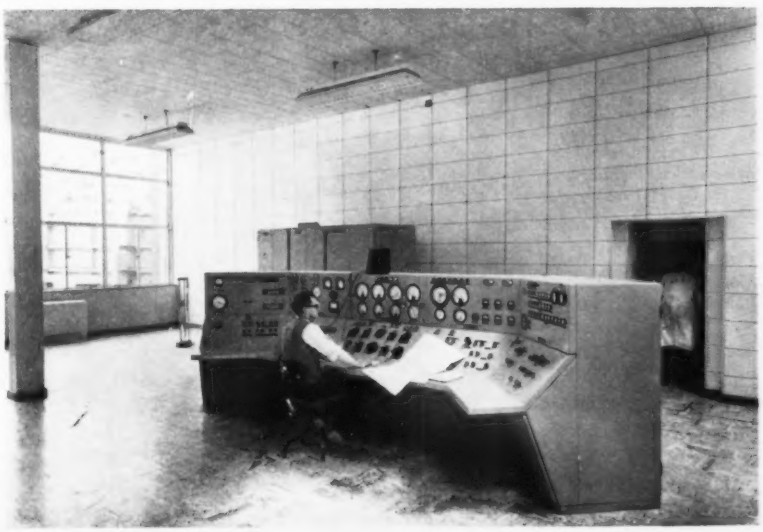
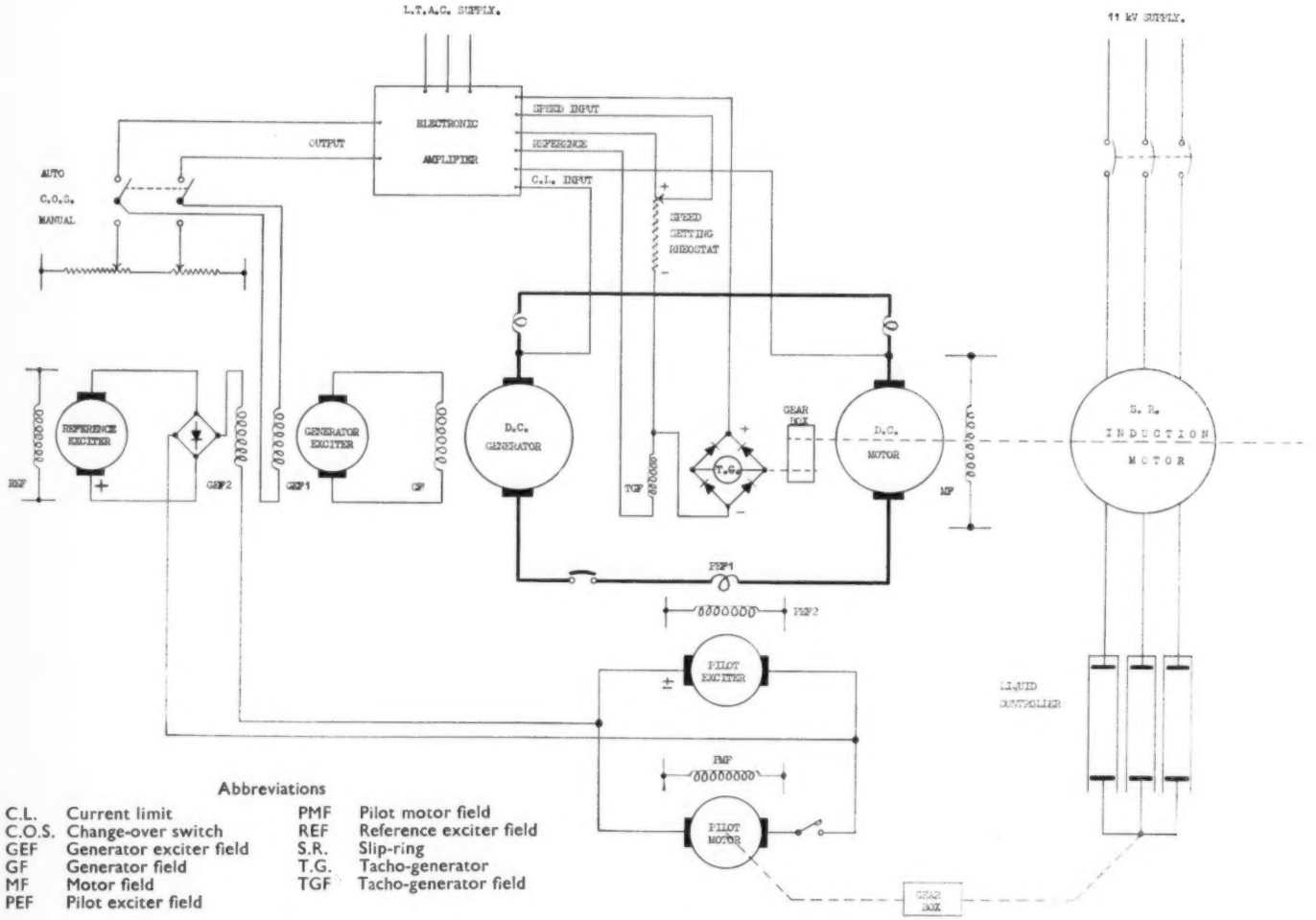


Fig. 6.—*Control desk in observation room*



Abbreviations

C.L.	Current limit	PMF	Pilot motor field
C.O.S.	Change-over switch	REF	Reference exciter field
GEF	Generator exciter field	S.R.	Slip-ring
GF	Generator field	T.G.	Tacho-generator
MF	Motor field	TGF	Tacho-generator field
PEF	Pilot exciter field		

Fig. 7.—Diagram of main electrical circuits

generated voltage is sufficient to close the rheostat pilot motor armature on to this exciter. The pilot motor then runs in a direction to alter the induction motor torque so as to reduce the D.C. motor torque to near zero.

The speed control and the current control form closed loop servo-systems which are stabilised by means of negative feeds back.

Torsional Vibration of Main Drive

Before the main drive was installed, an investigation was made to determine the possibilities of torsional vibrations at the natural frequencies of the drive. This kind of drive, consisting basically of two large inertias (fan and motor) coupled by a long shaft, tends to have a low natural frequency of torsional oscillation. A shaft failure in America on a similar drive had been attributed to this cause. The torsional oscillations can be excited by the slipring motor if the rotor phase resistances are not equal. With a liquid controller it is not possible to have exactly equal rotor resistances throughout the range, and any unbalance gives rise to oscillating torques at a frequency of twice the slip frequency of the motor.

The drive was analysed mathematically and it was found that there were two critical speeds within the working range at which an unbalanced liquid controller could cause large oscillations. Tests were therefore carried out as soon as the drive could be run to measure the oscillatory torques for various deliberately produced controller unbalances. Strain gauges were fixed to the fan and cardan shaft, and a torsiograph was coupled to the free end of the D.C. motor.

It was found that for the normal small unbalances in the liquid controller the oscillatory stresses which occurred at the critical speeds were not excessive and could be tolerated continuously without danger to the equipment. Nevertheless means have been provided to measure the balance of the motor rotor currents so that large unbalances can be detected before the shafting is damaged.

Compressor Drive

As mentioned previously, the walls of the tunnel are perforated and a small amount of air is drawn out near the working section (Fig. 1), making it possible to control the air speed around the speed of sound. The air removed amounts to between 3 and 8% of the total air flow. It is returned to the tunnel a short distance downstream of the working section, in the diffuser.

The pressure at the re-entry section is higher than at the working section so that a compressor is required which in this case has a compression ratio of 3·2 to 1. A large volume of air has to be transferred and hence considerable power is required by the compressor ; it is driven by a 13,750 h.p. two-hour rated synchronous motor, as shown in Fig. 8.

The motor is a salient pole machine designed for 11 kV, 0·9 leading power factor, 1,000 r.p.m., 9,900 h.p. continuously, and it drives the compressor through a step-up gear-box. The starting and synchronising is automatic and can be initiated from the observation room control desk. An auto-transformer reduces the applied voltage to the motor during starting, and the compressor is evacuated to a low pressure before starting in order to reduce the run-up torque.

The line breaker for the motor is an oil circuit-breaker unit forming part of the main metalclad switchboard in the switch room (Fig. 11). The motor protection consists of thermal overload, differential current, instantaneous overload, earth fault and under-power relays, all mounted on the panel of the main breaker. Another switchboard near the compressor contains the ' run ' and ' star point ' oil circuit-breakers for starting by means of the auto-transformer, and has panels for excitation and control. A part of this switchboard can be seen to the left of Fig. 8. The closing of the ' run ' breaker is controlled by a timing relay. The motor reaches synchronous speed in just under one minute from closing the line breaker. The D.C. field excitation is provided by a flexibly coupled exciter, and is switched on under the control of an automatic synchronising relay.

The motor bearings are forced lubricated, and oil jacking is employed during starting. Cooling air for the motor is drawn into the ends of the machine from the compressor house and discharged outside the building through trunking from the base of the motor.

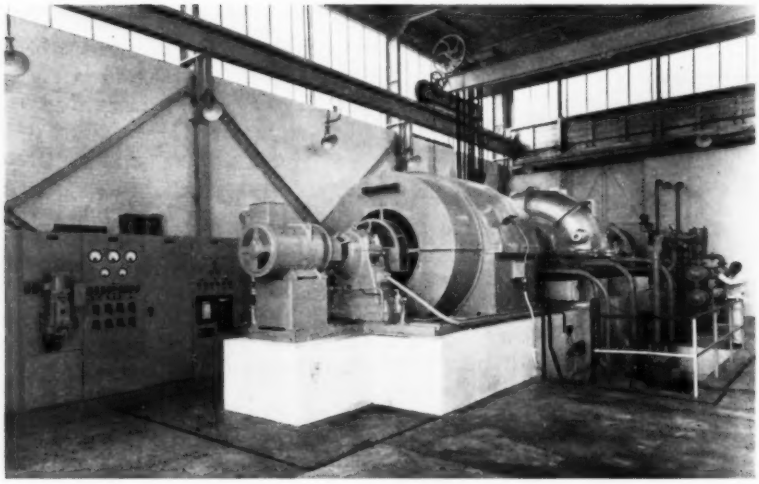


Fig. 8.—The compressor driven by a 13,750 h.p. synchronous motor

The leading power factor of the compressor motor is designed to compensate for the lagging power factor taken by the main drive induction motor, as these two machines will usually be running at the same time. The air circuit from the compressor has however been arranged to supply a smaller supersonic tunnel quite apart from the main tunnel. This smaller tunnel will have a working section 2¼ feet wide by 2½ feet high and will cover a speed range between 1·6 and 3·4 times the speed of sound.

Flexible Wall

In order to attain air speeds above about 1·2 times the speed of sound, the size and power of the compressor would normally have to be considerably increased, and it is therefore more economical to build into the tunnel an adjustable nozzle which can produce supersonic speeds before the air reaches the working section. In the A.R.A. tunnel this nozzle consists of flexible roof and floor plates with rigid straight side walls in a portion of the tunnel just ahead of the working section (Fig. 1).

Fig. 9 shows part of the flexible wall mechanism, including one of the cross members carrying the flexible roof-plate of steel strips, three of the vertical slides to which the cross members are pivoted, and cams against which the slides are held up by means of ropes and pulleys. The profile of the flexible plate is thus determined by the cams.

In order to change the nozzle profile from one shape to another a number of carefully synchronised and ordered operations must be performed, and all these are carried out electrically and automatically by simply selecting the desired nozzle shape on a stud switch giving nine distinct operating positions for the throat.

Tension in the ropes is provided by A.C. torque motors operating holding drums. The profile cams are driven by electric actuators of the 'English Electric' industrial linear screw type, and are positioned accurately by a limit switch which also provides interlocking. The correct sequence of operations is controlled by a master limit switch driven by a pilot motor, which in effect provides an analogue of the position of the throat, and is mounted in the control board for the flexible wall together with the control relays and contactors. The scheme has been designed to be as far as possible 'fault proof', so that if a torque motor should fail or a cam not position correctly, the master limit switch immediately stops, preventing further movement of the mechanism until the fault is rectified. A supply failure stops the operation but upon the power being restored the equipment can be re-started at exactly the same position in the sequence.

Flap Control

The two stages of the fan each have pre-rotational vanes on the upstream side. Both sets of vanes

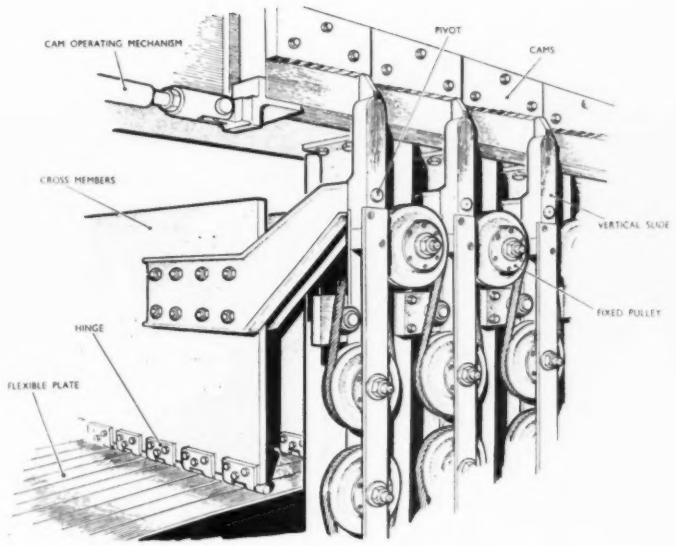


Fig. 9.—Part of the flexible wall mechanism of the wind tunnel

have trailing edge flaps which can be altered over an angular range from + 10° to − 20° from the normal. By altering the angle of air flow into the fan, the power output of the fan can be varied, at a given speed. This gives an alternative method of air speed control, and unlike motor speed control the moving flaps have little inertia.

Each set of flaps is driven by a vertical spindle slipring induction motor, and as it is important that both sets move in synchronism, the two motors are connected to form a synchronised drive, i.e. their speeds are precisely the same, irrespective of load differences or load fluctuations. Both stator windings are connected in parallel across the 415 volts 3-phase supply, and the sliprings of both motors are connected to a common resistance, so tying together the equivalent rotor phases. Synchronised running is possible so long as the stator windings are connected to the supply. For stopping the two motors in synchronism, a common 'stalling' resistance is switched into the rotor circuit a short time before the supply to the stators is removed; this ensures that the motors do not accumulate a displacement due to differences in friction each time they are stopped.

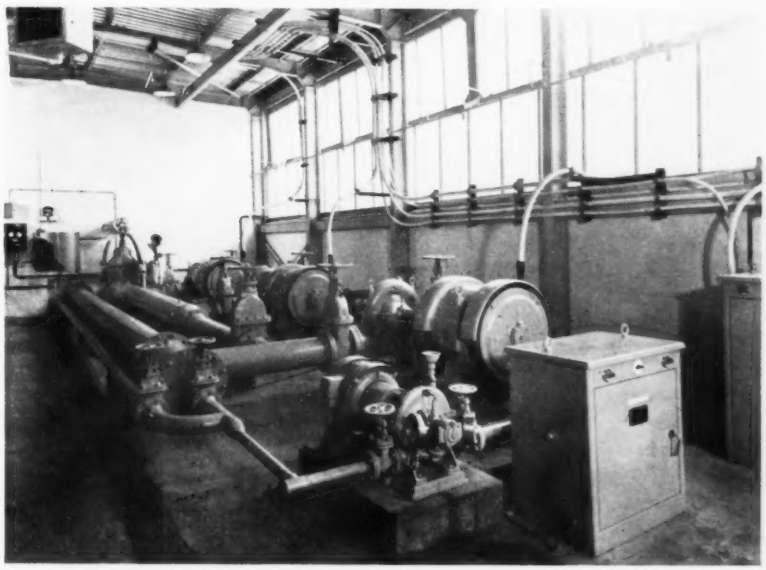


Fig. 10.—The three cooling water pumps driven by 140 h.p. squirrel-cage motors

It has been proposed to provide in the future an automatic load control operating on the flaps in response to a signal derived from tunnel pressure. This is to work in conjunction with the fan speed control, which it is not intended to replace.

Auxiliary Plant

Water Cooling

The power required to drive the tunnel is converted into heat, which must be continuously removed to maintain an acceptable air temperature, and for this purpose a cooler, which is an air-to-water heat exchanger, is positioned in the tunnel between the fan and the working section.

Other coolers are provided for the auxiliary suction plant just downstream from the compressor and for the electrolyte of the large liquid controller. The cooler for the latter must absorb heat equivalent to a maximum of 3,500 h.p. when the fan speed is 350 r.p.m. with the stator blades set for maximum power.

The water is circulated through all of these coolers by three main circulating pumps (Fig. 10), each capable of supplying 3,300 gallons per minute against a head of 100 feet, driven by 140 h.p. squirrel-cage motors which are direct-on-line started. The heated water is passed through a cooling tower into a reservoir for re-circulation.

Drying Plant

It is essential that the air in the tunnel is dry, because at high air speeds any water which condenses may cause shock waves to form and thereby interfere with the uniform flow of air past the model. A moisture content of 0·001 lb of water per lb of air is required, which corresponds to a humidity of about 10% at 50°C.

Small auxiliary compressors have been installed to keep the tunnel pressure slightly above atmospheric pressure, and the air is dried by passing through two alumina driers, one fed continuously with a portion of the tunnel air and the other drying any make-up air.

Switchgear and Control Board

Two views of the switchroom are given in Figs. 11 and 12.

The former shows the main 11 kV 250 MVA metalclad oil-break switchboard controlling the incoming supply from the Grid via a 30 MVA 132/11 kV transformer, and the outgoing circuits to the 25,000 h.p. fan motor, 13,750 h.p. compressor motor, the driving motor of the motor-generator set, and a 1,000 kVA 11 kV/415 volt transformer for auxiliaries.

Fig. 11.—Main 11 kV 250 MVA metalclad switchgear

Fig. 12 shows the main control board, which includes (from left to right) protective equipment and controls for the 132/11 kV Grid transformer and its tap-changing gear, one of the two 415 volt air-break fuse-switchboards for auxiliary motors and various power requirements, electronic control cubicles for the Ward-Leonard circuits, alarms panel, control and exciter cubicles for the main fan drive, and a control desk for the main drive auxiliaries.

Tunnel Measurements

Stress measurements on the model are made by means of resistance strain gauges which for

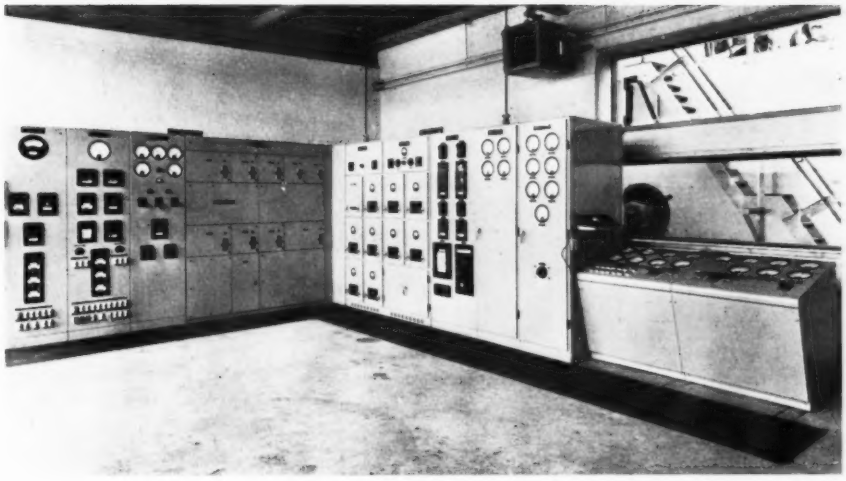


Fig. 12.
The main control board

recording purposes are converted into electrical impulses by a digitiser. Relays convert the signals into ordinary binary form and also act as a storage. The results are punched on cards and shown on a graphic plotter in decimal form.

Direct visual observation of a model is limited due to the holes in the perforated walls, and because the introduction of a glass window in the perforated plate would cause a disturbance in the air flow, a television camera is used. This camera is mounted inside the pressure shell, viewing the model through one of the holes in the perforated plate and showing it fully to the operator on a screen near the control desk.

Computation of Results

A digital computer is used to correct the data obtained from the wind tunnel into the form applicable to the design of full-scale aircraft. This takes the punched cards and performs all the necessary calculations, producing another card punched with the correct coefficients. The output system will feed up to 100 cards per minute, and these can be fed into a reader which operates an electric typewriter to type out a table of coefficients. Later a graph plotter is to be installed.

Acknowledgements

The authors are indebted to the Aircraft Research Association Limited for permission to reproduce the two drawings shown in Figures 1 and 9 and for information regarding the operation of the tunnel and the auxiliary equipment.

Napier Rocket Engines

FOR SEVERAL YEARS the intensive development of rocket engines for guided missile propulsion has been one of the secret activities of D. Napier & Son Limited under contract to the Ministry of Supply.

Napier rocket engines have been used to propel many of Britain's experimental guided missiles, both in this country and on the Woomera Rocket Range in Australia. Now the Napier Company is developing a range of liquid propellant rocket engines specifically designed for high-speed aircraft.

As a source of extra power at high altitudes where the jet engine delivers only a fraction of its sea-level thrust, or as a prime mover, this new series of rocket engines represents an important development in the realm of high-speed flight.

Rocket Engine Development

During the past seven years, the Napier rocket team at the Flight Development Establishment, Luton, has designed and tested several types of rocket engines. Their success has been due to the sound original conception and a continual development of the same propellant combination and principle of operation.

Since 1950 the Napier Company has made a considerable contribution to basic rocket engine design by carrying out an extensive test programme on combustion chambers, liquid cooling systems and burner head configurations. Parallel to this, other research has continued on auxiliary power units, turbo-pumps and control valves for rocket engine propellant systems.

These activities have resulted in one of Britain's most extensive rocket test installations being built at Luton. Special test houses have been constructed for proving the components of propellant systems, including a massive 100G centrifuge capable of testing the operation of propellant tanks and control systems at simulated high rates of

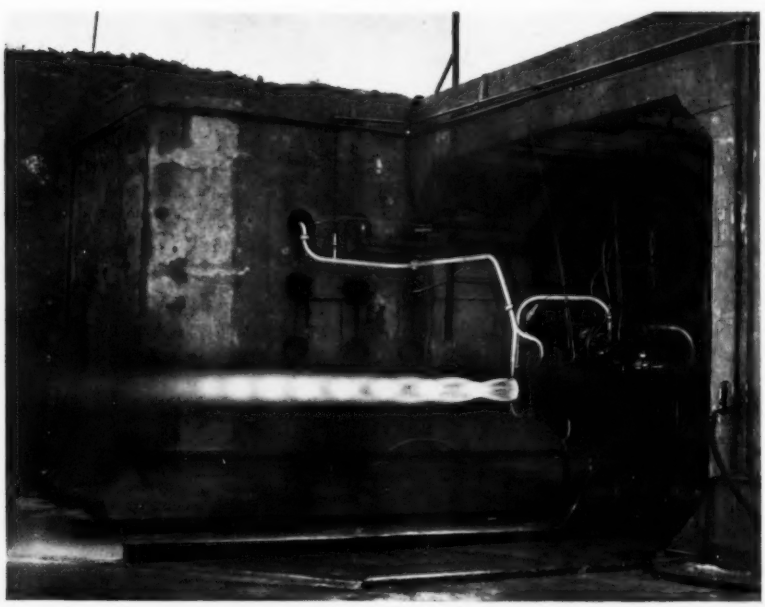


Fig. 1.—*An experimental rocket engine undergoing static firing tests on one of the Napier rocket test beds at Luton*

Fig. 2.—A batch of Napier NRE.11 missile rocket engines awaiting dispatch to the Woomera Rocket Range, Australia

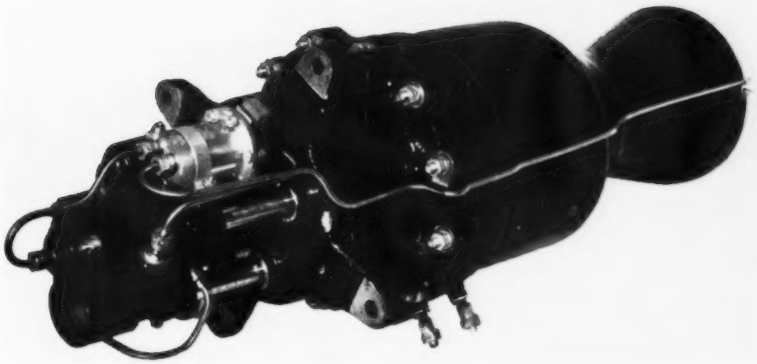


Fig. 3.—The Napier NRE.17 missile rocket engine designed for quantity production and developing a thrust in excess of 2,000 lb

manoeuvre. Among the many test emplacements are enclosures for testing turbo-pumps, rocket engine firing sites (Fig. 1) and an underground test bed for ground running a complete missile.

Rocket Engines for Missiles

One Napier rocket engine, the NRE.11 (Fig. 2), was put into small-scale production in 1952 for the propulsion of guided missiles. The engine was of the bi-propellant thermal ignition type and produced a two-stage thrust, full thrust being in excess of 2,000 lb. Electrical initiation of the propellant system enabled either thrust grade to be selected in flight, or the engine could be stopped and re-started at will.

In service, this early rocket engine proved to have high performance and complete reliability. It presented no major problems in production as no unusual materials or manufacturing techniques were used in its construction.

A new rocket engine of similar performance has been designed specifically for the propulsion of guided weapons. This engine, the NRE.17 (Fig. 3), takes advantage of the latest developments in uncooled combustion chambers and exhaust nozzles to make it suitable for quantity production. This engine can be produced in less than half the time needed for its predecessor, and its installation is simplified by its lighter and more compact design.

Rocket Engines for Aircraft

In contrast to the short-duration missile engine, the Napier Scorpion N.Sc.1 aircraft rocket engine is designed for sustained firing and a long operational life. In view of the engine's importance in

Fig. 4.—An 'English Electric' Canberra converted into a flying test bed for the Napier Scorpion N.Sc.1 aircraft rocket engine

Britain's rocket programme, details and illustrations of the Scorpion may not be published at present.

After prolonged static firing tests, the Scorpion is now installed in the fuselage of an 'English Electric' Canberra aircraft (Fig. 4) for flight trials and further development. The first air firing was successfully carried out in May 1956, and has been followed by an extensive series of firings undertaken at a wide range of altitudes.

The Scorpion aircraft engine represents the accumulative result of many years of rocket research and development along logical lines, and inherits stamina, simplicity and complete reliability from its earlier missile counterparts.

Considerations in the Design of Outdoor High Voltage Substations

By A. R. PARISH, B.Sc.(Eng.), A.M.I.E.E., Assoc. Mem. A.I.E.E., Switchgear Engineering Department.

PART I

IN THE DESIGN of an outdoor high voltage substation a number of interrelated problems have to be solved before it is possible to arrive at a layout which is both technically sound and economically attractive. This article presents some of the factors which require consideration before the design of the substation can be completed.

It may be useful for those not familiar with installations of this nature first to explain generally their purpose and composition. Substations are centres for the control, transmission, and distribution of electric power, including voltage transformation. For voltages of 33 kV and upwards it is very common practice to install the equipment outdoors in order to avoid the cost of buildings. This equipment will include circuit-breakers for the interruption of fault current, isolators for disconnecting circuits for maintenance, busbars and connections for interconnecting the circuits, insulators, supporting structures and other ancillary items, and usually also power transformers. All these have to be co-ordinated to provide a satisfactory substation, and the fact that the equipment is exposed to the elements adds to the problems involved.

Electrical Circuit Arrangements

A large number of alternative electrical arrangements have been designed to provide maximum facilities at minimum cost. In all cases the following technical points require to be considered :—

1. Is easy maintenance possible without interruption of supply or danger to staff ?
2. What alternative facilities are available if there is an outage on any of the apparatus ?
3. Can the station easily be expanded if the load grows ?

It is also necessary to recognise that apparatus which is included to cover a very remote contingency may itself introduce further possibilities of failure and so reduce, rather than increase, the reliability of the arrangement.

With these points in mind it is interesting to consider some of the schemes at present in use.

Single Busbar

The single busbar scheme (Fig. 1) is the simplest,

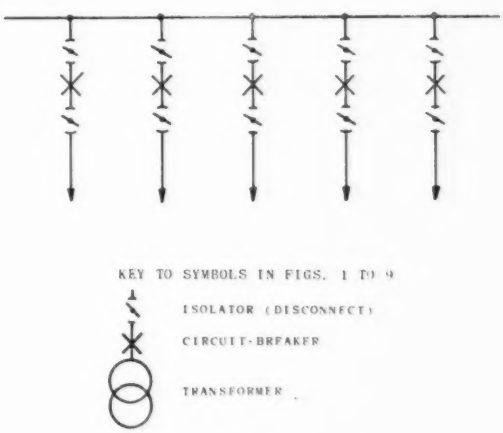


Fig. 1.—*Simple single busbar scheme*

and consequently the cheapest, of all, but unless the loads can be fed from some alternative source no maintenance can be done without interruption of supply. Similarly it is not possible to extend

the station without a shut-down. However, the simplicity leads to convenient operation since there is the minimum of complication in equipment connections.

Single Busbar with Bus-section Switches

With a bus-section switch (Fig. 2) the restrictions

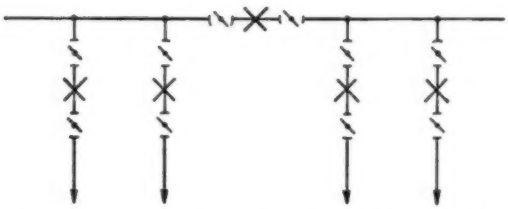


Fig. 2.—Single busbar with section circuit-breaker

of the single busbar arrangement apply to the sections individually, but any outage can be confined to one section of the equipment. To obtain the best service from this scheme it is essential to divide incoming and outgoing circuits evenly between the sections, and to arrange that where two feeds go to one load they come from separate sections of the busbar.

Where isolators are used for sectioning they may only be operated off-circuit ; this may cause operational problems in attempting to obtain zero current flow across the section to allow them to be operated. These problems disappear if a bus-section circuit-breaker is used, and the use of a circuit-breaker rather than an isolator allows any bus-zone (bus differential) protection to trip only the faulty section without shutting down the whole substation.

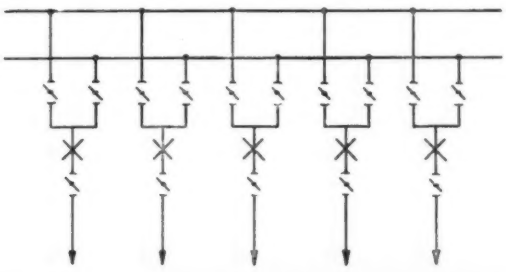


Fig. 3.—Double busbar scheme

Double Busbar

In this scheme (Fig. 3) each load may be fed from either busbar and so it is possible to divide loads and infeeds into two separate groups if this is required for operational reasons. It is also possible to connect all circuits onto one bar, so freeing the second bar for insulator cleaning or extension. If on-load change-over from one busbar to the other is required it is necessary to add a bus-coupler circuit-breaker since the normal selection isolators cannot be used for breaking load current.

This scheme has been very widely used, particularly for those systems which are so arranged that individual circuits may be released from time to time for maintenance.

Double Breaker Scheme

The conventional double busbar layout does not allow for breaker or isolator maintenance without outage, and the simplest way of overcoming this disadvantage is the use of the double breaker

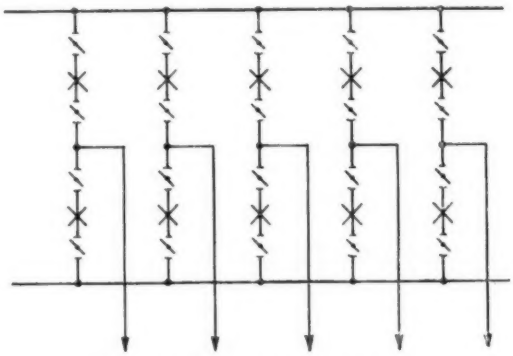


Fig. 4.—' Double breaker ' scheme

scheme (Fig. 4). This permits either breaker to be made available for maintenance, but unless duplicate isolators are used in series it is not possible to work on isolators without a shut-down.

Although this arrangement is simple and satisfactory it is very expensive. Consequently almost its only application is for very large generating plant where security of connection is paramount.

Breaker-and-a-half Scheme

This scheme (Fig. 5) economises in the number

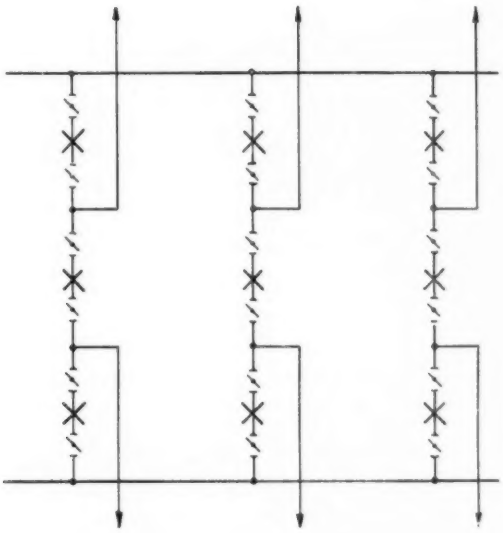


Fig. 5.—' Breaker and a half ' scheme

of circuit-breakers while providing virtually all the facilities of the double breaker scheme. There is however a complication, in that the protection must associate the central breaker with the correct feeder.

Main and Transfer Busbar

Whereas the double busbar arrangement allows a busbar to be taken out of service without outage but does not permit a circuit-breaker to be maintained, the main and transfer busbar scheme (Fig. 6) provides exactly the opposite facility. Any one circuit at a time can be switched to the transfer bus, and the protection transferred to the bus-coupler breaker, but the main busbar cannot be made ' dead ' without an outage. If therefore the service is such that considerable breaker maintenance is envisaged, this scheme is attractive, but again the isolators cannot be maintained without a shut-down. Because the connection to the transfer busbar is through isolators, careful interlocking is necessary with the bus-coupler breaker.

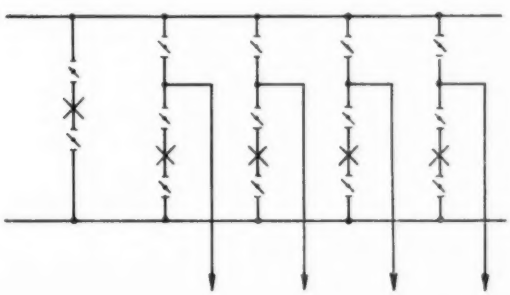


Fig. 6.—Main and transfer bus scheme

By-pass Isolator Scheme

A method which provides the facilities of both ' double bus ' and ' main and transfer bus ' is the addition of a by-pass isolator to the double busbar scheme (Fig. 7). Either bar may be used as a main busbar, and one of the bars can act as a transfer bus. There is some complication in the layout, and an additional isolator is normally required for each circuit.

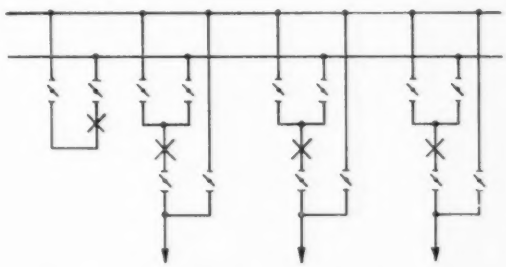


Fig. 7.—Double busbar with by-pass isolators

Since the by-pass facility is only required infrequently, some capital expense may be avoided by omitting the by-pass isolator while making provision for temporary jumper connections to by-pass the circuit-breaker. It is of course necessary to shut down the circuit while the jumper connections are fitted and the normal connections dropped off the circuit-breaker.

Mesh Scheme

The mesh scheme (Fig. 8), which is known as the ' ring bus ' in North America, has the appearance of possessing almost all the desirable features, but on close examination many of them prove to be illusory and the scheme has many serious limitations from the operational and safety aspects.

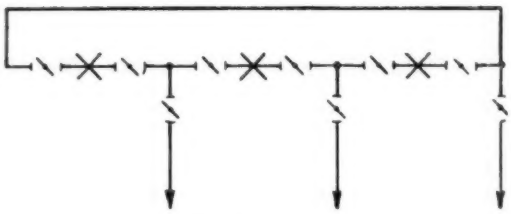


Fig. 8.—Mesh scheme or ' ring bus '

So long as the mesh is closed each feeder has two sources of supply and any circuit-breaker may be taken out of service without affecting the supply. If however a second breaker opens in these circumstances a number of circuits will be lost, and for this reason the mesh scheme should be limited to four or six circuits. The extension of a mesh station beyond the number of circuits initially provided for is virtually impossible.

To measure the current passing to an individual feeder it is necessary to compare the currents from two sets of current transformers which have to be capable of carrying the current passing round the mesh while the feeder current, represented by the difference current, may be small. This makes for considerable difficulty in obtaining accurate values of current on feeders of low rating.

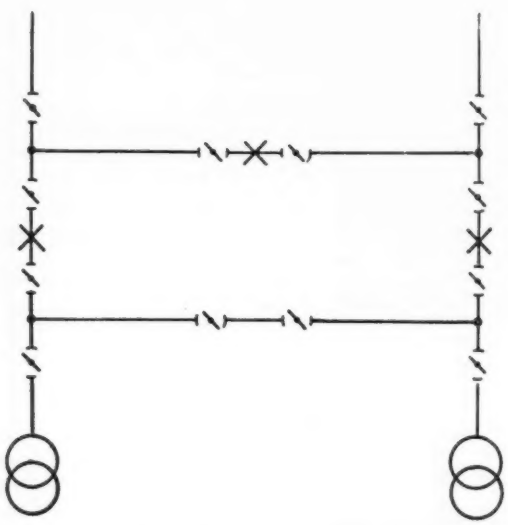


Fig. 9.—Three-switch station

The necessity to trip two circuit-breakers to clear a feeder fault complicates the protective wiring and may cause safety problems, since current transformers in an otherwise ' dead ' circuit will be made ' alive ' from another circuit-breaker carrying current. One attractive feature however is that all the sections of conductor in the station are covered by the feeder protection and, there being no busbars as such, there is no need for bus-zone protection.

Three-switch Station

This type of station (Fig. 9) does not readily fall into any of the previous groups but it is worthy of consideration since it permits an economical initial installation with possibilities of expansion.

Under normal operating conditions all three circuit-breakers are closed and the by-pass isolator circuit is open. Switching a transformer requires two circuit-breakers to be operated whereas line switching requires the operation of one circuit-breaker. This arrangement is chosen because the incidence of line faults is greater than that of transformer faults. If local circumstances so require, however, there is no objection to interchanging the positions of lines and transformers. Any of the breakers may be taken out of service for maintenance at the expense of some temporary loss of flexibility of operation.

The physical layout of the substation may be so arranged that the initial three-switch arrangement subsequently forms part of a normal single busbar station. There is of course some complication in the operation of the station, but interlocking has been devised which avoids any danger.

Physical Layout

For outdoor substations three basic types of layout may be recognised, namely, high, intermediate and low, each of which may have numerous minor variations.

High Type

In this design (Figs. 10 and 10a) a very substantial structure, almost invariably of steel, carries nearly all the switchgear apparatus apart from circuit-breakers and voltage transformers. Such an arrangement is very economical in ground space at the expense of using a large amount of structural

steel. Because of the height and compact nature, maintenance is difficult without extensive shut-down and in many cases operation is made more difficult by problems of visibility. Where sites are restricted, as in high head hydro-electric developments, it may be the only possible type to use, and it may also be economic if site costs are very high.

It is also interesting to note that the high type of layout is not as suitable for a double busbar arrangement as the low or intermediate types. With the high type the two sets of busbars are arranged one above the other, so that any flashover on the lower set of bars will almost inevitably involve the upper set as well. Thus the security of supply to be expected from a double busbar arrangement is prejudiced.

Intermediate Type

This type of station (Fig. 11) uses individual structures either of steel or reinforced concrete to support the isolators, and separate structures are

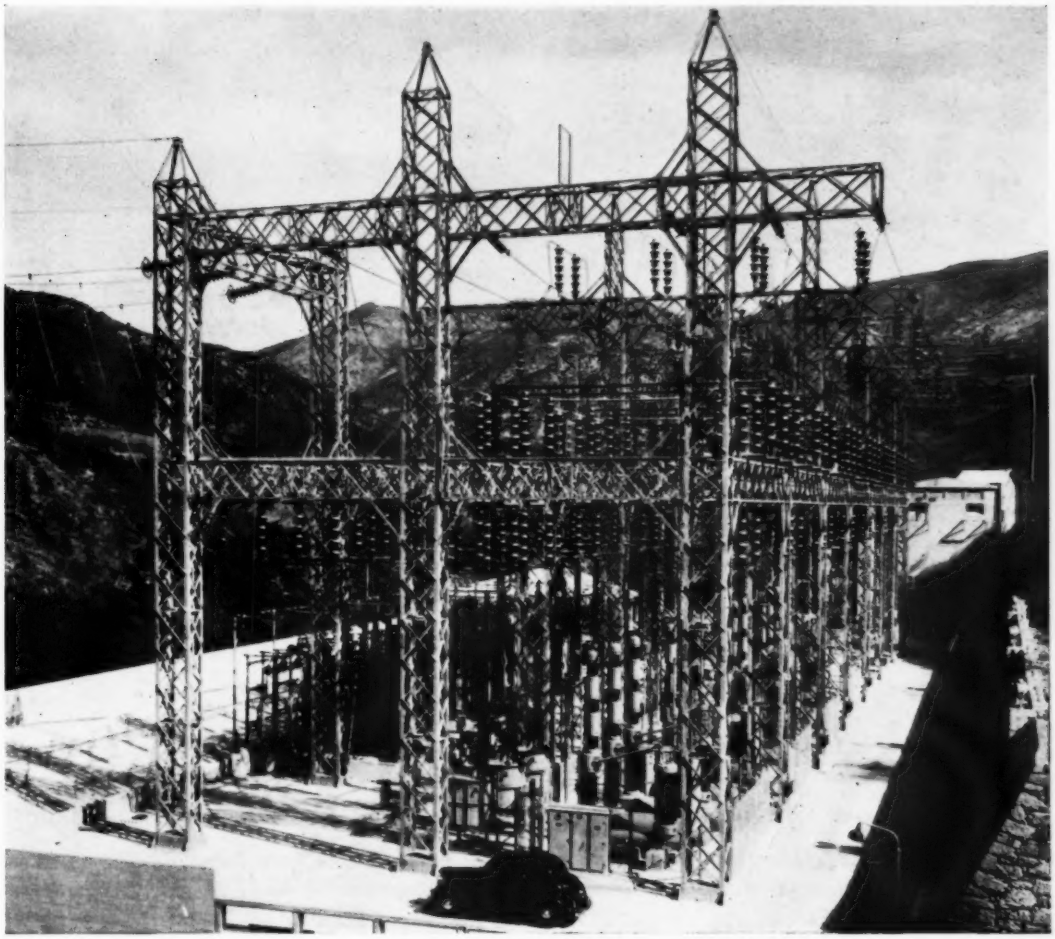
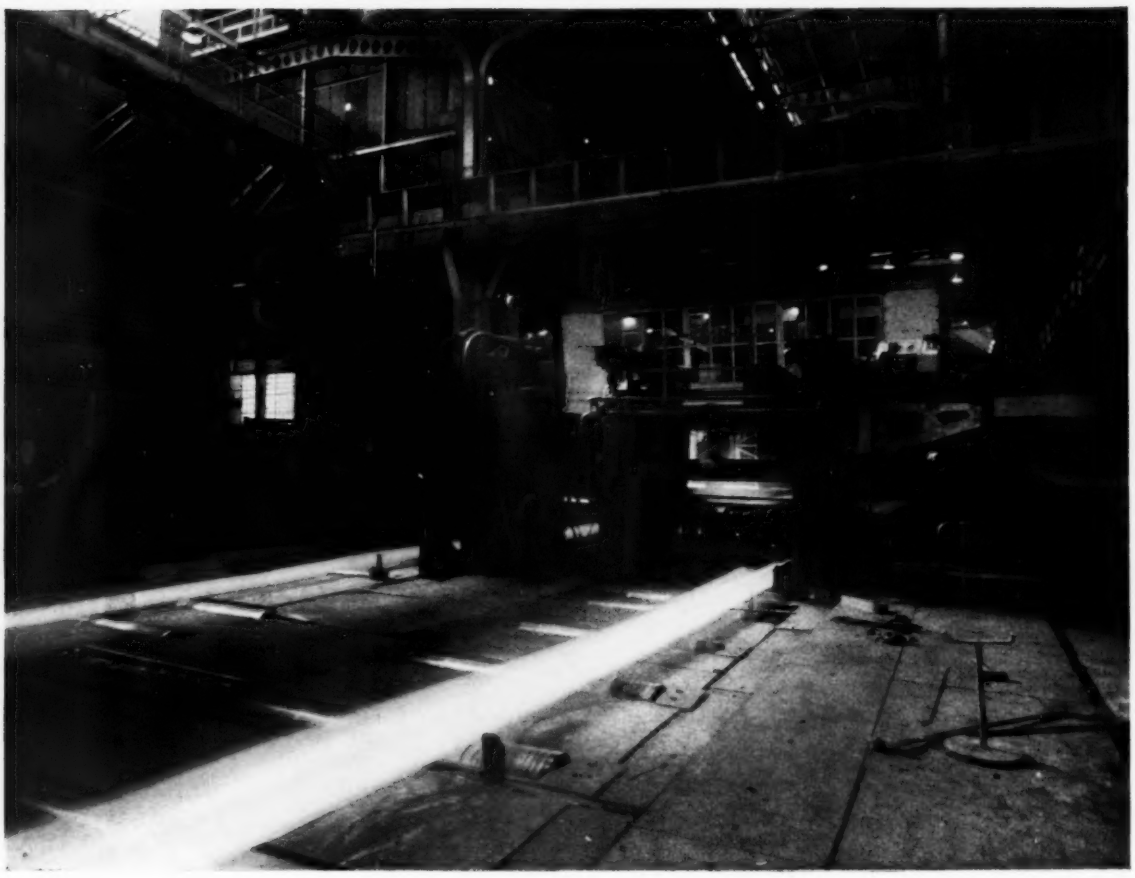


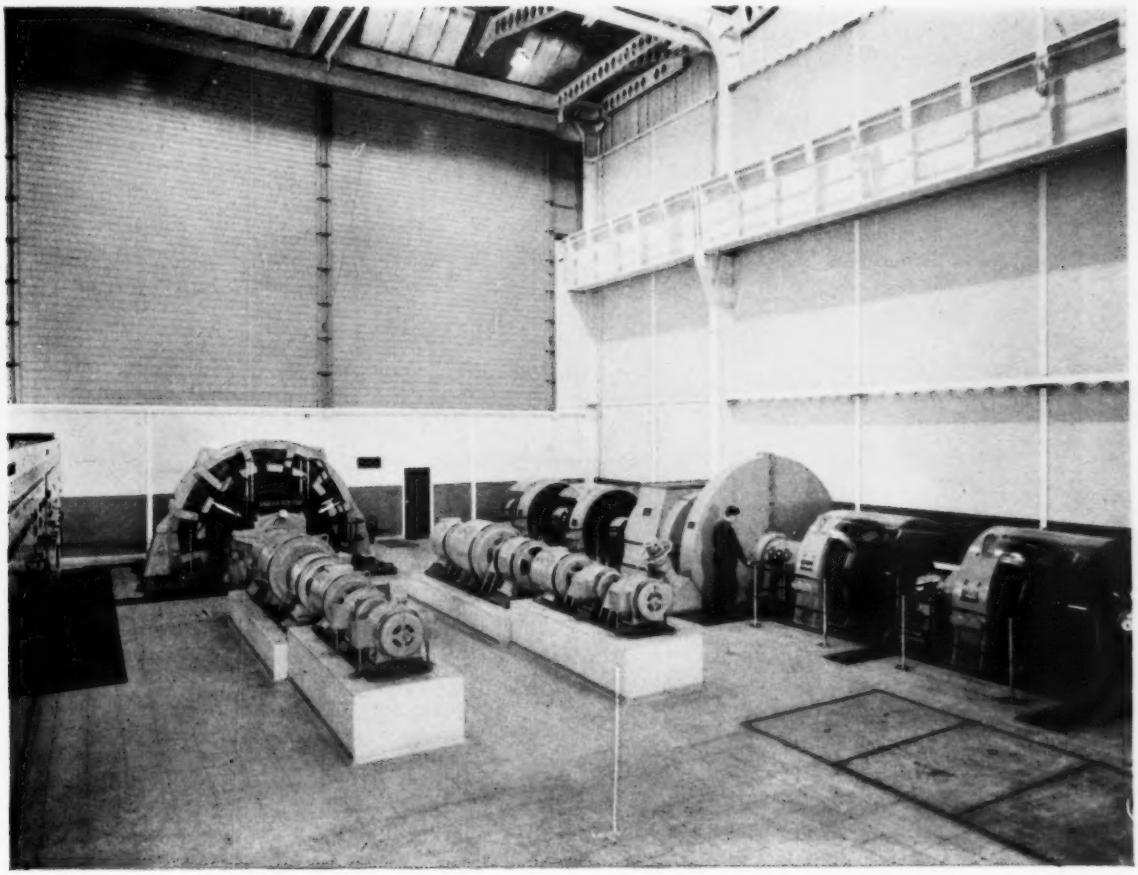
Fig. 10.—*The* 165 *kV high-type substation at Vila Nova, Portugal, containing three* 30 *MVA generator transformers and air-blast switchgear*



The two mills illustrated are the 34-*inch roughing and the* 30-*inch finishing mills, producing* 95*lb/yard r*
Electric Company, are controlled from the pulpit on the bridge-like structure in the background. The rou

The right-hand illustration shows the motor room for these mills, containing the common Ilgner set, exciter

During her West Cumberland tour in 1956, *Her Majesty The Queen opened the world's first commercial-scale a*
of Workington Iron and Steel Company and the local power line of the Central Electricity Authority's Grid,



/yard r the Workington Iron and Steel Company. These mills, which were electrified in 1956 *by The English The rou l drive is rated at* 2,750 *h.p. and the finishing mill at* 2,500 *h.p.*

exciter s control gear and the finishing mill drive motor.

scale at gy power station at Calder Hall. Later Her Majesty put into operation a link between the electrical system s Grid, ing these works the first steelworks in the world to be powered by means of atomic energy.

used to support the busbars which are of the strained type using flexible conductor. The maximum height is considerably less than with a high station and so concrete structures, which are usually limited to a height of 45 feet, become possible.

Low Type

This design (Fig. 12) carries the ideas of the intermediate type a stage further since separate supports for the busbars are eliminated. The busbars, which in this case have to be of the rigid tubular type, are supported on one side of the isolators, but as the distance from isolator to isolator is equal to the bay spacing of the switchgear and is generally greater than can be spanned in one jump by a rigid bar of normal size, an intermediate support is required.

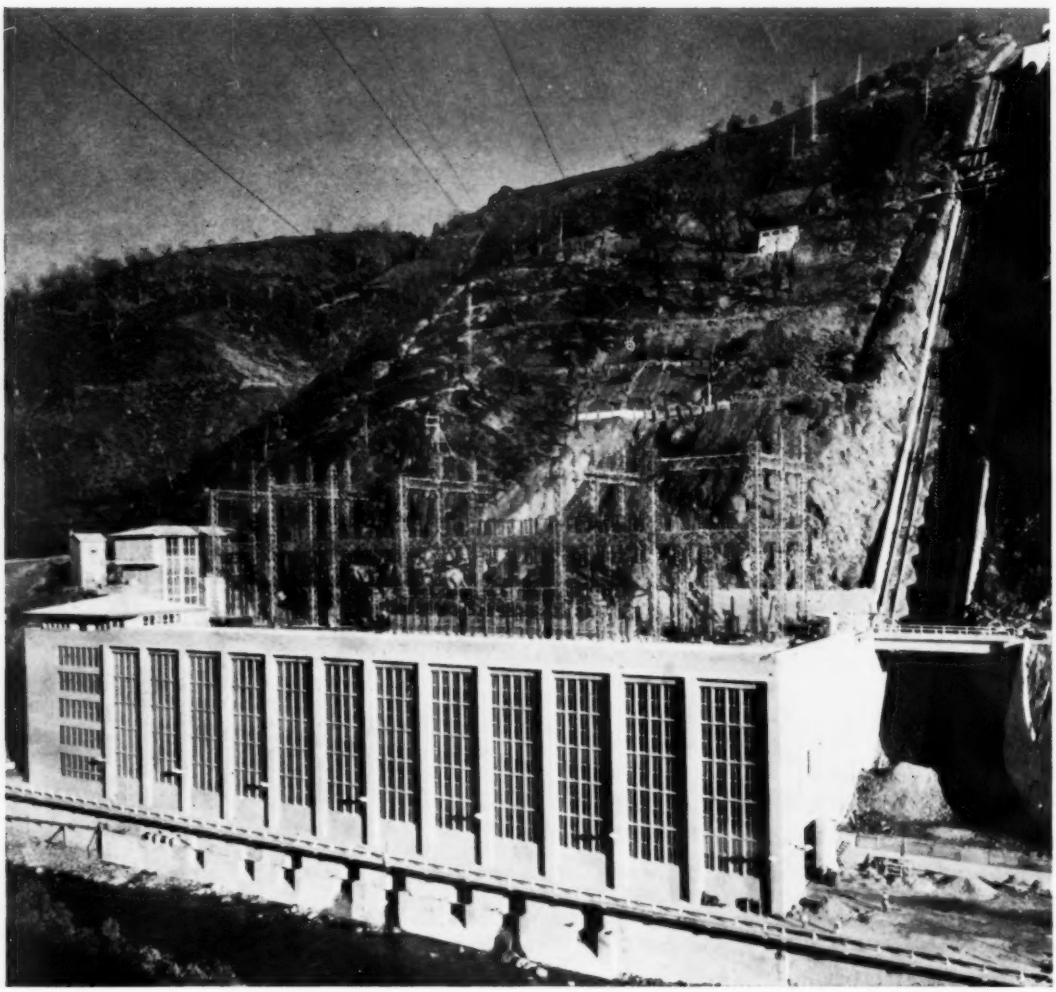


Fig. 10a.—Another view of the 165 kV substation shown in Fig. 10, with the Vila Nova hydro-electric power station below

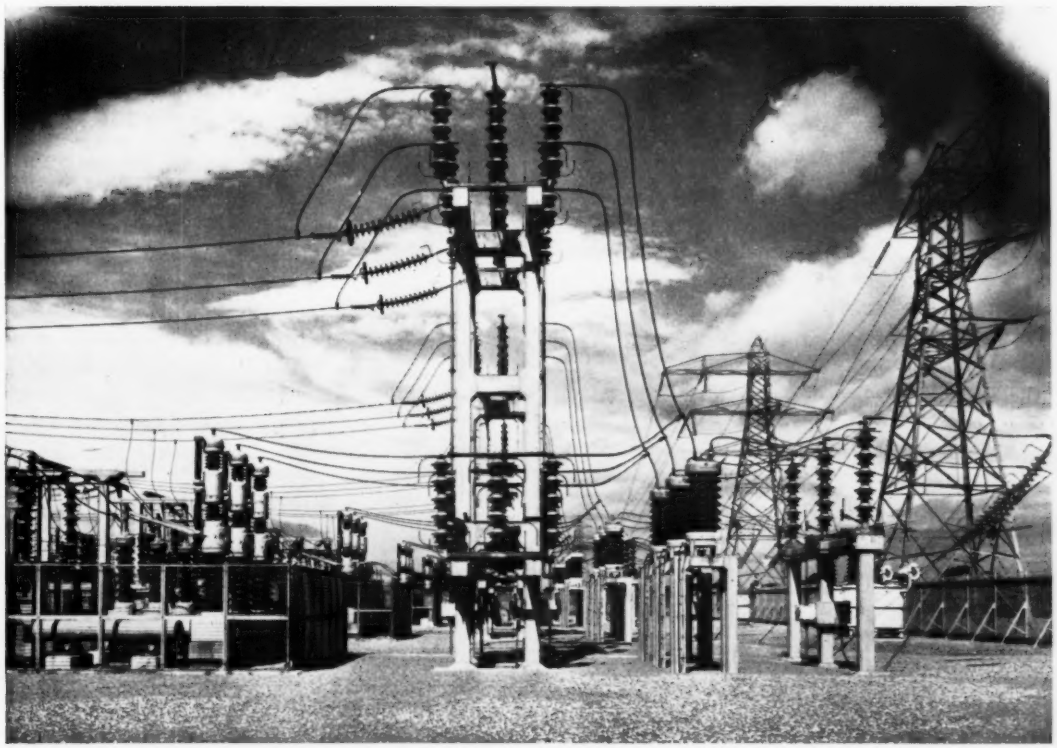


Fig. 11.—A 132 kV intermediate-type substation of the British Central Electricity Authority, equipped with air-blast circuit-breakers

The low arrangement does of course use a large site area, which may be a disadvantage. On the other hand only simple structures are required, maintenance is simplified and the simple layout assists in safe operation and maintenance.

Lightning Protection

There are two fundamentally separate lines of defence in providing lightning protection for sub-station apparatus. The primary defence is to prevent the lightning stroke terminating on a conductor, by judicious use of overhead earth wires or rods, while the secondary defence is the use of surge diverters (lightning arresters) or co-ordinating gaps to provide a path to earth for lightning current. However, the cost of protection needs to be related to the probability of lightning damage and it is therefore necessary to have some measure of the severity of lightning. Normally the only information available is the ' isoceraunic level ', that is the number of days in the year on which thunder is heard, and this may be taken as a rough and ready indication although it gives no guide to the severity of individual storms. For comparison it may be noted that the isoceraunic level in Britain is about 15, in the U.S.A. from 10 to 90, in Canada generally below 30 and in the tropics up to 100.

Where the probability of lightning damage is appreciable a screen of earth wires or vertical rods is provided so that lightning will strike these rather than substation apparatus. The degree of protection provided depends on many factors, including cloud height and the nature of the terrain, but it has been estimated that 99·9% protection will be provided with a protective angle

of 45° (Fig. 13) for a single earth wire, or 60° where more than one wire is provided. A protective angle of 30° is often used when lightning rods are employed. It is however expensive to provide this protection, and in Britain it is not usual to put an earth screen over substations.

The earth wires commonly used over high voltage lines also provide considerable protection for substations. They prevent direct strokes reaching the line conductors and hence the substation apparatus. So far as substation protection is concerned they need only extend for about half a mile ; strokes to the transmission line beyond this distance will be sufficiently attenuated before they reach the substation so that they will not cause

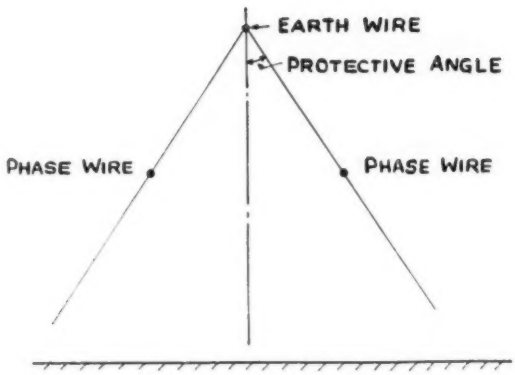


Fig. 13.—*Protective angle of earth wire*

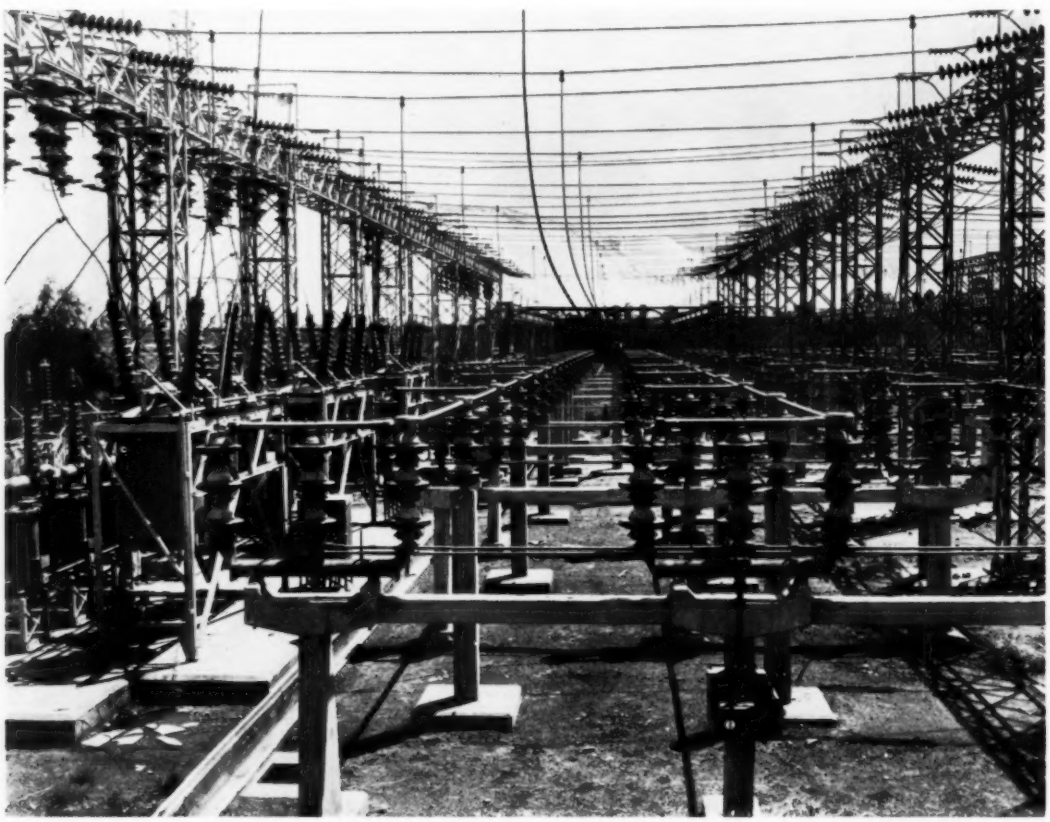


Fig. 12.—*An* 88 *kV low-type substation in South Africa, equipped with oil-break circuit-breakers*

trouble if suitable lightning arresters or co-ordinating gaps are used.

Surge diverters are used to provide a path to earth for lightning current which will not have an adverse effect on the substation apparatus and will not result in a fault on the system. Their construction is such that while the lightning current is passed to earth the power-frequency current which would follow the same path is stopped. Since surge diverters are connected from line to earth, the voltage rating necessary depends on the maximum line/earth voltage to be expected under normal conditions. Where a system is ' effectively earthed ' the maximum line/earth voltage is, by definition, limited to 80% of the system line/line voltage, and diverters of reduced voltage rating may be used. In a few special cases even lower rated diverters may be permissible.

Where the cost of surge diverters cannot be justified by the incidence of lightning, co-ordinating rod gaps may be used instead. They have the disadvantages that when they flash over they cause a system outage, and they may not give satisfactory protection against surges of very steep wave front. The latter point is not significant if incoming lines to the substation have overhead earth wires.

Clearance and Creepage Requirements

Until comparatively recent years the design of equipment and installations subject to lightning had to be based on performance under power-frequency (normally 50 cycle) high voltage tests, although in fact system-frequency over-voltages of the magnitude used for testing could not possibly occur in service. The knowledge gained of the nature and behaviour of lightning however has led to the introduction of impulse voltage testing of high-voltage equipment and to insulation co-ordination being based primarily on impulse performance.

The magnitude and wave shape of lightning strokes vary greatly and it has therefore been necessary to lay down standards of wave shape for impulse testing. The British standard impulse voltage wave has a front of 1 microsecond and a time to half-value of wave tail of 50 microseconds, as shown in Fig. 14. This is normally referred to as a 1/50 full wave and its voltage is specified by

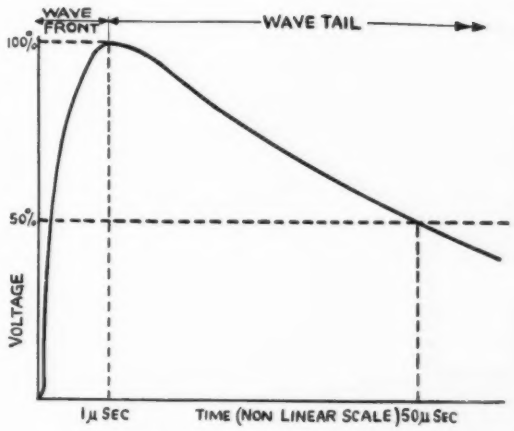


Fig. 14.—1/50 *microsecond impulse*

the maximum amplitude or peak value. The impulse may be either of positive or negative polarity. The American standard is a $1\frac{1}{2}/40$ wave, but in most practical cases test results are very little affected by the slight differences between the two standard shapes. The tolerances on the time to crest and to half value permitted by British Standard 923 : 1940 (' Impulse Voltage Testing ') are such that a $1\frac{1}{2}/40$ wave just lies within the B.S. tolerance limits of a 1/50 wave.

For most apparatus it is necessary to know the ' impulse withstand ' value, since this is the maximum voltage at which breakdown of insulation does not occur under impulse test. Standard impulse withstand voltage levels have been laid down in British Standard 116 : 1952 for outdoor type oil circuit-breakers, and are given in Table I.

TABLE I

Rated Service Voltage kV	Impulse Withstand Test Voltage	
	Non-effectively earthed system kV	Effectively earthed system kV
22	150	150
33	200	200
44	250	250
66	350	350
88	450	450
110	550	450
132	650	550
165	750	650
220	1,050	900
275	—	1,050

These impulse insulation levels are generally applicable to transformers as well as switchgear. They compare closely with American standard basic insulation levels (BILs) and those determined by practical experience of protection levels afforded by surge diverters.

It is not of course practicable to carry out impulse tests on a complete substation, and so clearances must be based on laboratory tests simulating the worst conditions which may be expected in practice. Recent work has shown that the lowest flashover value for a given clearance is obtained between the top cap of a post insulator and a vertical earthed screen. This arrangement does not normally occur in practice, and one slightly less onerous, with a positive impulse applied to a rod suspended above an earthed plane, forms the basis of the clearances. The clearances obtained to provide the necessary impulse withstand levels on this basis are given in Table II and have been used by The English Electric Company for some time. These figures provide, in practice, a very considerable margin of safety, so that where good surge protection is used and the incidence of lightning is low, there may be good economic grounds for using slightly smaller clearance values. Suitable figures are given in Table III.

TABLE II

FOR NORMAL CONDITIONS

Impulse Withstand Level kV	Minimum Clearance to Earth in Air inches
150	12
200	16
250	22
350	30
450	39
550	48
650	54
750	66
900	75
1,050	84

The main consideration in choosing phase/phase clearances is to ensure, so far as possible, that any flashovers that occur are phase/earth and do not develop into phase/phase faults. Thus the phase/phase clearances are normally made 15%-20% more than the phase/earth clearances. Table IV gives some commonly used values. In practice, a station layout is often not greatly affected by reasonable changes in the phase/phase clearance value, since the spacings are largely determined by the necessity to preserve satisfactory clearances with isolators in the open position.

TABLE III

FOR FAVOURABLE CONDITIONS

Impulse Withstand Level kV	Minimum Clearance to Earth in Air inches
150	11
200	15
250	19
350	27
450	34
550	42
650	50
750	58
1,050	82

TABLE IV

System Voltage kV	Phase/Phase Air Clearance inches
33	18
44	23
66	33
88	43
110	53
132	63
165	78
220	108

Phase/earth and phase/phase clearances are chosen to permit satisfactory operation of the system, whereas safety clearances are intended to permit men to work on 'dead' apparatus without danger from adjacent 'live' equipment. It is therefore necessary to make sure that under all normal conditions a man cannot get any part of his body nearer to live metal than the phase/earth clearance. For this purpose it is assumed that a man standing with his arm stretched upwards can reach a height of some 8 ft and consequently, to make it possible to walk under apparatus, this is set as the minimum height of the lowest unearthed

part of any support insulator. Adding this figure of 8 ft to the phase/earth clearance gives the approximate value of the safety clearance to live metal (Table V gives the exact figures to which this Company normally works). This safety clearance must be maintained from any position where a man may reasonably be required to work to the nearest point on an adjacent circuit which may be alive.

TABLE V

System Voltage kV	Safety Clearance inches
33	108
44	114
66	120
88	126
110	132
132	138
165	150
220	168

The use of these values of safety clearance does assume that men will not be permitted to use long tools or to deviate from normal working positions on or about the equipment ; otherwise they are obviously endangered. Thus safety clearances depend to a large extent on the operating practice of the equipment user, and variations from normal British practice may be found in other countries. In this connection it is interesting to note that the United States National Electric Safety Code bases its safety clearances on the assumption that a man can reach 8 ft 6 in vertically but only 3 ft 6 in horizontally. In many ways this seems a more logical method and reduces station size, but it does reduce the safety margin if a man should overbalance.

There are two other points concerning station insulation in air which require consideration ; they are the effects of altitude and pollution.

The effect of altitude is to lower the flashover voltage in air compared with the performance at sea level, while puncture and flashover under oil are unaffected. However, switchgear and transformers to British Standards are suitable for use up to 3,300 ft ; above this height the present requirement is to increase the impulse withstand voltage and wet withstand voltage of the apparatus, as tested near sea level, by 3·5% for each 1,000 ft in excess of 3,300 ft. Clearances in air are similarly increased. However, opinion is forming that 3·5% per 1,000 ft is too severe, and a figure of 3% is likely to come into use before long.

In industrial and coastal areas the solid matter in the atmosphere is attracted, by the electric field, to the insulator surfaces and may form an adherent coating which is not easily washed off by rain. These coatings may not have any adverse effect when dry, but when damped by fog or drizzle they form partially conducting paths and may predispose the insulator to flashover. Unfortunately it has not been possible so far to carry out accelerated tests in the laboratory to check the performance of a particular insulator under these adverse conditions, and the normal wet test with clean insulator surfaces is not indicative of performance when dirty. The only method by which good performance in polluted conditions can be ensured has been found to be the specification of minimum creepage lengths on the insulators. For normal conditions, and in Britain this covers areas where up to 90 tons of industrial dirt is deposited per acre per year, a creepage distance to earth of $\frac{3}{4}$ inch per kV of system voltage has proved satisfactory, e.g. 88 inches for a 132 kV system. For more serious industrial pollution and in coastal areas the specified creepage length is increased to 1 inch per kV of system voltage, and in this case at least half the specified creepage distance should be protected against rain at right angles to the insulator. This latter provision is intended to keep at least half the creepage length relatively free from damp deposits of dirt, but there is a school of thought which considers this a wrong approach and advocates generous vertical insulation surfaces which can easily be washed by rain ; this view is supported by the practice of using power insulator discs in tension rather than in suspension strings because of the improved washing by rain of insulators with a substantially horizontal axis.

In addition to the normal ' cap and pin ' insulator used in multiple assemblies for high voltage work, the solid-type post insulator is also favourably regarded. It has the attraction of long leakage paths without complicated shed formation.

Structures

Both concrete and steel structures are commonly used, and the choice between the two materials depends on a number of considerations, some of which are noted below :—

Concrete :

Low maintenance costs—needs no painting.
Economic if substantial numbers of similar structures are required.
Limited to about 45 ft height.
Not practicable to ship overseas.

Steel :

May require periodical painting even when galvanised.
May be built to any height or size required.
Economic when only small numbers of similar structures are required.
May be shipped overseas or, if required, local constructional engineers can often manufacture.

Concrete structures are convenient and economical only where an identical design can be used for a number of substations, as only in this way can the cost of the patterns be recovered. The elimination of painting is an advantage with concrete structures, but because of height limitations they can only be used for 'low' and 'intermediate' type stations. They must be manufactured near the point of use since their weight and fragility adds to transport costs, and carriage by sea is quite uneconomic.

Steel structures can of course be designed for any arrangement of substation, and steel is the only practicable material for the 'high' type. In many parts of the world local manufacturers can fabricate suitable steel structures, but often their price is not competitive with that for structures exported from the United Kingdom.

The cost of any substation structure depends very much on the conditions of wind and ice loading which may occur and the factors of safety which are used. Practice in these respects varies but the figures of Table VI, based on British conditions, are often used. Modifications are necessary in tropical areas where, while ice loading does not arise, hurricanes may be encountered. For steel structures it is usual to specify a minimum metal thickness to guard against undue weakening by corrosion, and $\frac{3}{16}$ inch for galvanised work and $\frac{1}{4}$ inch for painted work are typical. The use of galvanised structures is general, since the cost of galvanising is relatively small compared with the saving in maintenance costs by reducing the frequency of painting. However, in areas where corrosion of steelwork is not rapid, the saving by omitting galvanising and relying on painting may be worth consideration.

TABLE VI

Wind and ice loading figures commonly used for British conditions

Wind pressure	25 lb/sq ft
Ice loading	$\frac{1}{2}$ inch radial thickness
Factor of safety	2·5
Maximum L/R ratio :	
Main members ..	120
Other members ..	200

The use of pre-stressed concrete structures has received some consideration but this type has not so far been used in Britain.

Earthing

In any substation it is necessary to provide an earthing system both for safety earthing of structures, tanks etc. and for earthing the system neutral when this is required. All uses of the earthing system however have the same requirements, namely, that it should itself have a low impedance and be as effectively tied to true earth as is reasonably possible.

The earthing system normally consists of copper strip which may be fixed to the sides of trenches or run in the ground. In trenches, bare strip is often used, but when laid direct in the ground some bituminous or plastic serving is normally applied as a protection against corrosion, particularly in 'made-up' ground. So far as possible the main layout is arranged in the form of closed loops with spurs off to individual pieces of apparatus. The main earth bars may of course have to carry the full earth fault current of the system in the event of a line/earth fault, and a size of strip must therefore be chosen which will safely carry this

current for the maximum time of operation of the protective equipment. It is good practice to follow this principle even where resistors or reactors are used to limit the earth fault current, since these devices might fail at the crucial moment. The section of bare strip may satisfactorily be chosen on the basis of a temperature rise of 400°C after 3 seconds, and this gives a current rating of approximately 80,000 A/sq in. Ordinary soft solders will melt at 400°C and it is therefore essential that sweated joints should also be riveted or that brazed joints be used. Where the strip is served or other organic insulation comes into contact with it a lower designed temperature rise may be necessary. Connections which are unlikely to carry the full short-circuit current may be of smaller section, but it is unwise to use less than 1 in $\times \frac{1}{8}$ in strip because of the danger of mechanical damage.

Rod, plate or pipe electrodes may be used for the actual connection to earth. Rod electrodes are easy to drive, particularly if an electric hammer can be used, and are valuable where a high-resistance stratum overlies low-resistance strata. However, the current rating is low, of the order of 100-150 amp for a 12 ft rod, so that many rods are necessary. Further, experience shows that when long rods are required and two sections are screwed together without sweating or brazing, the results may be unsatisfactory. There seems to be little advantage in using star or cruciform shaped rods rather than circular sections. Plate electrodes, consisting of a 4 ft square heavy copper or cast iron plate set vertically in a coke bed, have a current capacity of 1,000-2,000 amp but are generally only applicable where low resistance strata are near the surface. Pipe electrodes are now rarely used, since the cost of excavation for an 8-10 ft pipe is excessive. Where there are large masses of steel, such as circulating water pipes, penstocks, sheet piling, steel framed buildings and structures, in contact with earth it is convenient to bond the earth system to them so that they help to provide the connection to true earth. In many cases such connections are required anyway for safety reasons.

Electrodes should generally be sited in small groups at various points about the substation site, each group being solidly bonded together but provided with a link for testing purposes between the group and the earthing system. Usually the substation earthing system is joined to the earth wires of incoming overhead lines ; if the earth wires do not come into the substation a cable connection is used. The substation fence should normally not be connected to the main earth system unless this system extends beyond the fence ; it should have a separate earth system of buried bare strip or driven rods adjacent to the fence line so as to avoid danger to the public during fault conditions in the station. Surge diverters and line-coupling capacitor equipment should have their own earth rods or plates immediately adjacent to them to minimise reactance at the high frequencies concerned. These electrodes should also be solidly connected to the main station earth system.

The object of all the precautions mentioned in this section is to tie the substation metalwork etc. down to true earth potential so far as practicable. However, both the earthing system itself and its connection to true earth have resistance which under fault conditions will cause a voltage drop, thus raising the substation potential above true earth. The resistance of the earthing system will normally be quite low and can in any case be made as low as required by adding copper. The connection to earth however is in a different class, since in some cases the geology of the area prevents a low resistance to true earth. So long as the resistance is low enough for satisfactory operation of the protective equipment the station itself will not suffer if the earth resistance is high. Under fault conditions, the area of the site will form a substantially equipotential plane, provided there is sufficient copper buried in the switch yard to produce an effective mat, and all personnel and apparatus will remain at the same potential. However, if the substation site rises in potential relative to earth, trouble may be experienced with fault current flowing in cable sheaths, and the breakdown of telephone apparatus is possible. To overcome such difficulties insulating cable jackets are feasible and transformers may be used in telephone systems, but the most satisfactory solution if at all possible is to obtain a low earth resistance.

This article will be concluded by Part II, to be published in the September 1957 issue of this journal, Volume 15, Number 3.

The Diesel-Electric Trawler 'Portia'

By N. P. BLACKBURN, M.I.Mech.E., M.I.Mar.E., Manager, Marine Projects and Contracts.

THE COMMISSIONING OF THE distant-water trawler 'Portia', in October last year, marked another stage in the advance of Britain's fishing industry. Built by Smith's Dock Co. Ltd for Hellyer Brothers Ltd of Hull, she is the first British commercial trawler to be fitted with diesel-electric propulsion machinery, and this was supplied by The English Electric Company. In itself this change in engining is a big departure from tradition, and in this ship it is accompanied by many new features, carefully blended with all that experience has proved essential in distant-water trawlers.

Service Conditions

Fishing vessels face the severest weather conditions which exist at sea and the worst are those met by the distant-water fleet. The all too familiar radio warning, "gales are expected in sea areas . . . ", tells of normal conditions from October to April on the fishing grounds where these ships operate. Fishing ceases only when it is no longer safe to work on deck, or when the temperature is so low that the fish freeze before they can be cleaned.

These trawlers work in winds up to 30 m.p.h. and temperatures down to zero Fahrenheit. When

Fig. 1.—*The diesel-electric trawler 'Portia'*

it is no longer possible to fish, the ships 'ride it out' or seek quieter areas where they can continue to work. They enter no port during their voyage, and only return home when they have made a catch which will show some profit. A distant-water trawler spends 18 to 21 days at sea each trip, 9 to 12 days of which are spent on the fishing grounds. The voyage to and from the grounds is made at full speed, regardless of sea conditions. These ships are at sea for about 300 days each year, and surveys, docking and machinery maintenance are all done in the home port. There is neither the opportunity nor the staff to attend to the machinery at sea, and so it must do all that is asked of it, continuously, since one lost trip can turn a profit into a loss over the year.

Apart from high winds and seas, sub-zero temperatures add to the hazard ; spray freezes on to decks, rigging and superstructure, and 'black frost' coats the upperworks with ice weighing many tons. Such additional top weight affects the stability of a vessel, and ships have been lost by capsizing on this account. The crews endeavour to keep the weight of ice down by cutting it clear with axes and hot water hoses, but since this is not always possible the real margin of safety lies in the inherent stability of the ship.

From the first, distant-water trawlers have been powered by steam engines : a standard reciprocating engine, developed for the industry out of long experience, and taking steam from a single 'Scotch' boiler, forms the usual propulsion unit. Simple and robust, steam driven auxiliaries have provided the ship and engine room services, and the trawl winch is also steam driven. This plant is simple and markedly reliable ; it presents no operating problems to the crew, and the industry's repair facilities can readily service it and keep the ships operating on a regular schedule. Such machinery does, however, have certain drawbacks ; its fuel consumption is high and the power is limited by the single boiler. As a result, the largest steam-engine-driven distant-water trawler which can be accommodated in Britain's fish docks has machinery of about 1,200 i.h.p. and burns approximately 10 tons of boiler oil per day, averaged over a trip. This limited power restricts the fair weather speed to about 12½ knots and, based on prices prevailing before the Suez Canal crisis, incurs a fuel bill of £24,600 per annum.

Design Considerations

It was against this general background that Hellyer Brothers Ltd, Smith's Dock Co. Ltd, and The English Electric Company began to consider the suitability of diesel-electric machinery for a new ship, then in the project stage. The ship was limited in size by the fish dock facilities to about 200 feet in length, and it had to carry at least as much fish as other vessels of its class and at a higher voyage speed. In addition to the inherent need for absolute reliability, economy in operation was desired to offset the higher machinery costs. It was also strongly emphasised that the ship should be as safe as experience and modern development could make it. During the summer months, the slack season for distant-water fishing, some trawlers do a three months trip catching and salting cod for the European market. The new ship was to have special facilities for this service, not least being the ability to operate for the whole trip on bunkers taken at the home port where fuel is cheapest.

It was decided that 1,500 s.h.p. could be applied economically to a hull of the necessary size and type, and should give a speed which would save about a day on each distant-water trip ; this could add up to an additional earning trip each year. The restricted size of the engine room permitted the use of diesel-electric machinery but limited the number of main generating sets to three, allowing for reasonable working and maintenance space.

In comparison with an orthodox steam-engine-driven ship the reduction in weight of machinery, bunkers and water arising from the use of diesel-electric machinery amounted to about 285 tons. This saving was used in the design of a hull to give an additional 33% freeboard, and improved lines offering a reduction in resistance to assist speed. The extra freeboard would make for a drier and safer ship less likely to have its fishing interrupted by bad weather.

The propelling characteristics of electric drive are at least as good as those of steam machinery, and a high order of reliability is achieved by the use of three engines ; with this arrangement power for the trawl winch is available from the main

engines, obviating the need for a special generating set for this duty. Fishing can continue with one engine shut down and, in extreme emergency, the ship can return home with only one engine running. The exceptional manoeuvrability provided by direct bridge control of the machinery was considered ideal for fishing, this control being much superior to the orthodox telegraph and voice-pipe orders to the engineers.

Although distant-water trawler engineers are for the most part ' steam ' men, there did not seem to be any reason why they should not be quite at home with a well designed diesel-electric installation, after a short training course. Similarly, the shore maintenance staff were expected readily to absorb the different practice involved in overhauling diesel engines and, since they normally deal with the comprehensive electrical auxiliary equipment in a modern trawler, would have no difficulty with the heavier machinery employed for propulsion duty.

Due to the extremely low temperature in which these ships must operate, the habitability of the engine room presented a problem of its own. The heat radiated from the orthodox steam plant is sufficient to keep temperatures in the comfort zone, and still allow the relatively low air circulation rate needed to revitalise the atmosphere. With a diesel installation a lower order of heat radiation is coupled with the need for an air supply sufficient to scavenge positively the machinery space of all noxious vapours, and for the engine induction requirements.

It was considered that trunking engine induction air from deck level would be desirable, since this would reduce the amount of air to be admitted to the engine room by more than 5,000 cubic feet per minute ; it would also permit the air change rate to be controlled by ventilation requirements. Calculations revealed that by using the exhaust air from the main generators as the primary source of ventilating supply, the volume of which can be adjusted in relation to temperature, engine room air change rates could be selected to maintain crew comfort when operating in very low temperatures.

Main Features

After carefully considering all factors the owners decided that the use of diesel-electric machinery would permit the construction of a vessel of advanced design which would have a performance much superior to that of existing ships of her type. To contain all requirements of crew and service she would be Britain's largest and fastest trawler, with the following salient particulars :—

Length overall	210 ft 6 in
Length B.P.	190 ft 0 in
Moulded breadth	34 ft 6 in
Moulded depth	17 ft 10 in
Gross tonnage	882 tons
Speed	15 knots
Fish hold capacity ..	17,500 cu ft
Bunkers	227 tons

Hellyer Brothers' ships are all named after Shakespearian characters, and the new vessel was christened ' Portia '.

As can be seen in Fig. 1 ' Portia ' is a graceful ship with clean upperworks and easy lines ; the superstructure presents a minimum wind area and the ' bipod ' mast dispenses with the heavy rigging normally carried on trawlers. The combined effect is to reduce considerably the foundation area on which ice can build, and consequently the resultant risk of loss of stability in the vessel. During last winter the worst weather in memory prevailed on the fishing grounds, and the ' Portia's ' performance in these severe conditions was outstanding. She not only continued to fish when more orthodox ships were weather bound but her voyage speed in these weather conditions was even higher than anticipated ; her financial return in this period reflects this performance.

Accommodation

Fig. 2 shows the general arrangement of the ship. The accommodation is on the port side and the generous space provided is the result of designing the ship for fishing to starboard only ; 30 officers and men can be accommodated in very comfortable conditions, the officers have individual cabins and the crew are berthed in spacious quarters on the lower deck aft. There is space available in the fo'c's'le for an additional crew of 14 if required on a salting voyage. It can be seen from this illustration that access to the engine room and main accommodation is by way of the boat deck and that it is possible to move from the

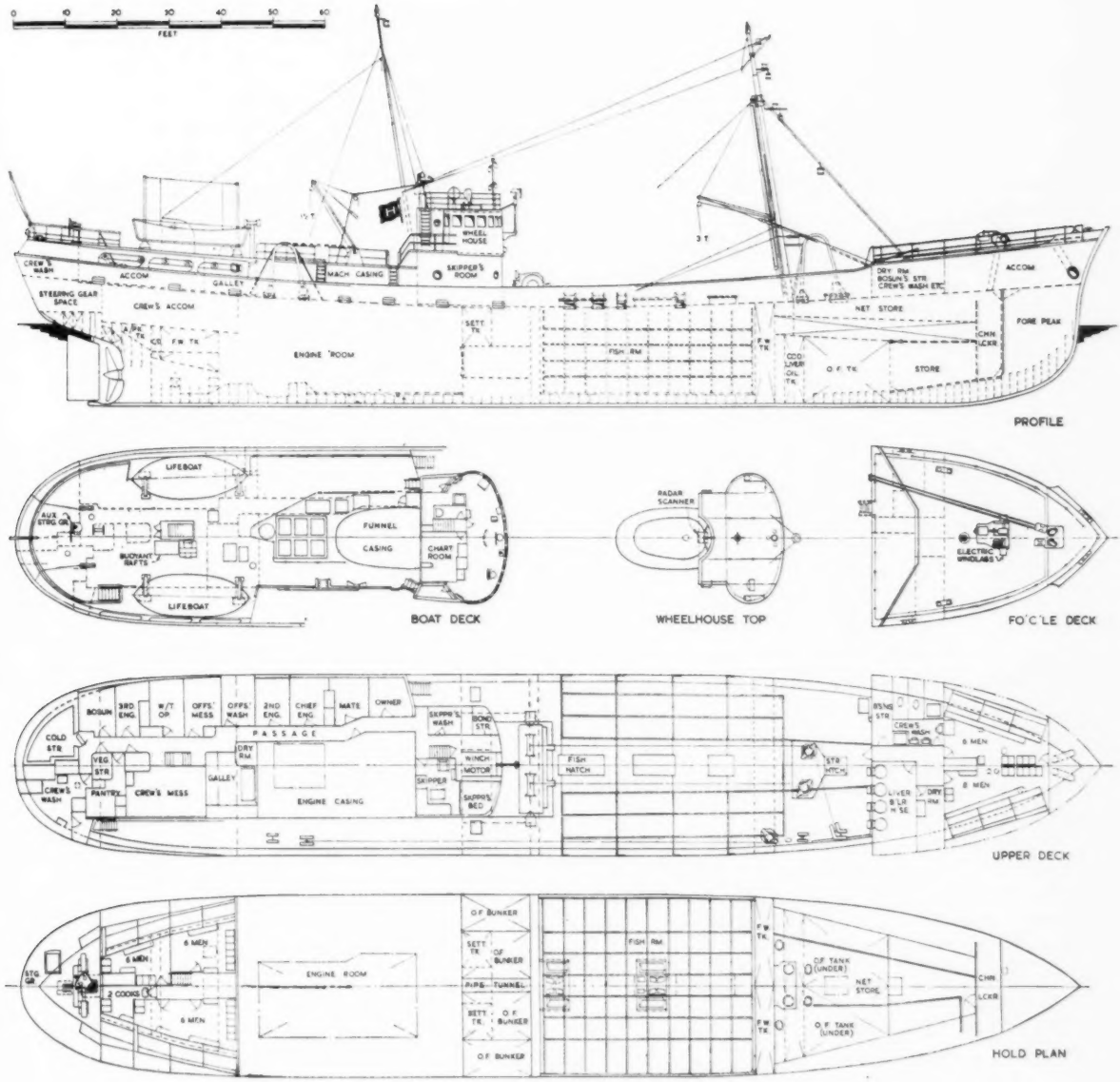


Fig. 2.—General arrangement of the ' Portia '

wheelhouse to the engine room and accommodation without going on to the exposed deck. These are safety precautions designed to prevent the entry of water into the deckhouse or casings and to permit the crew free movement in bad weather.

Wheelhouse

The wheelhouse (Fig. 5) is spacious, and square water-tight windows allow free vision for an arc of 240°. The starboard wing is the ' shooting bridge ' and contains a second steering wheel, an engine

room telegraph/controller and the 'Fishviewer' echo sounder display; this equipment is arranged so that the skipper can control the ship when fishing without leaving his chair. Remote loud-speakers with 'talk-back' facilities enable orders from the bridge to be transmitted to, and acknowledged from, all working stations about the decks.

Wireless Equipment

The Marconi International Marine Communication Co. Ltd, a member of the 'English Electric' Group, supplied to 'Portia' what is probably the most comprehensive wireless equipment ever fitted in a trawler. The radio is more powerful than that carried in most ocean going ships and ensures that contact can be established from the most distant fishing grounds. The installation comprises a 'Globespan' transmitter with an 'Atlanta' receiver for long range working; these sets also provide facilities for duplex radio-telephony with remote control in addition to their normal duties of medium- and high-frequency telegraphy. A separate 'Gannet' radio-telephone transmitter and a second 'Atlanta' receiver are equipped for voice-operated carrier working. Navigational aids include a 'Quo Vadis' radar with a 12-inch display and a 'Seapilot' direction indicator for taking bearings from radio beacons. Two 'Fishgraph' recording echometers are used as aids to fishing as well as for navigation, one of which works in conjunction with a 'Fishviewer' cathode ray tube to enable fish echoes to be scrutinised more closely. 'Loran' long range navigation equipment is also provided since there is one of these stations covering some of the area in which 'Portia' operates. The navigational aid equipment is largely located in the wheelhouse whilst the radio installation is in the chart room abaft of it.

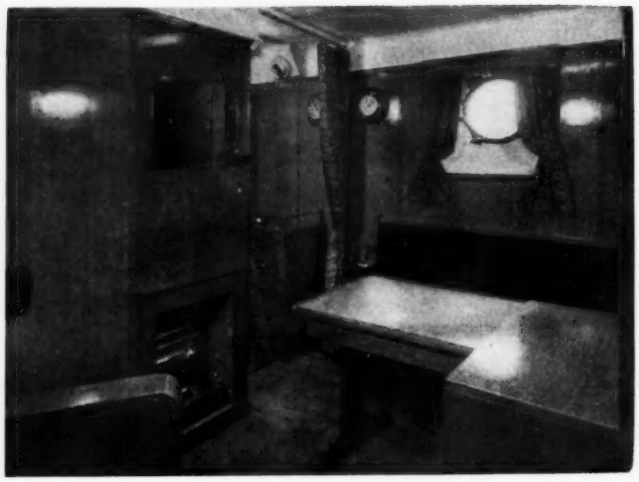


Fig. 3.—A corner of the skipper's cabin

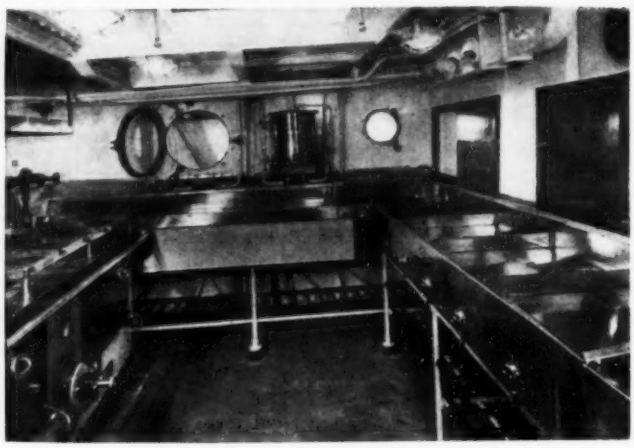


Fig. 4.—The galley

Trawl Winch

The trawl winch (Fig. 7) is mounted immediately forward of the casing and its 300 h.p. driving motor, together with its Ward-Leonard exciter set, is located inside the casing below the wheelhouse. This arrangement is the standard adopted for electric trawl winches since it gives the protection necessary to the electrical equipment without interfering with the free working space about the winch itself. James Robertson & Sons built the winch, which is their Bear Island (Andenes) type arranged to carry 750 fathoms of warp on each of the two winch barrels. This length of warp is quite

normal and arises from the need to run out 3 fathoms for every fathom depth of water in which the ship is fishing.

Propulsion Machinery

'Portia's' propelling machinery is basically a standard 'English Electric' three-engined direct-current diesel-electric installation, suitably adapted for this class of ship. It does, however, contain some features specially developed to meet the space limitations and the severe service conditions in which the ship operates.

Fig. 5.—The wheelhouse, with the 'shooting bridge' on the right

It was decided that the simple controlled-voltage principle of operation, using a modified Ward-Leonard system of control, would be most suited to the arduous operating conditions and would permit the use of the standard Ward-Leonard controlled trawl winch used generally in middle-water trawlers. As a result of this decision, and space limitations, a new type of 'set up' switch was developed. This is of the 'draw out' type and can have three operating positions, 'Propulsion', 'Trawl' and 'Off'. The propulsion control gear was re-designed to reduce the space occupied and a new 'follow up' system adopted for the bridge control equipment. These developments met, in all respects, the service requirements and produced a very compact yet completely accessible main control board.

Fig. 6.—Part of the Marconi wireless installation

Cooling and Air-conditioning Systems

The decision to draw the engine induction air from deck level created a problem in that diesel engines do not operate satisfactorily in extremely

low air temperatures, especially when lightly loaded. Further, sea water temperatures fall to 28°F where this type of trawler operates, and cooling systems, especially in oil circuits, can cause a great deal of trouble in these conditions. The power requirements fluctuate widely when fishing and include periods of no-load operation. It is not practical simultaneously to tend the plant and control temperature changes arising from these variations in output which occur over short-time intervals.

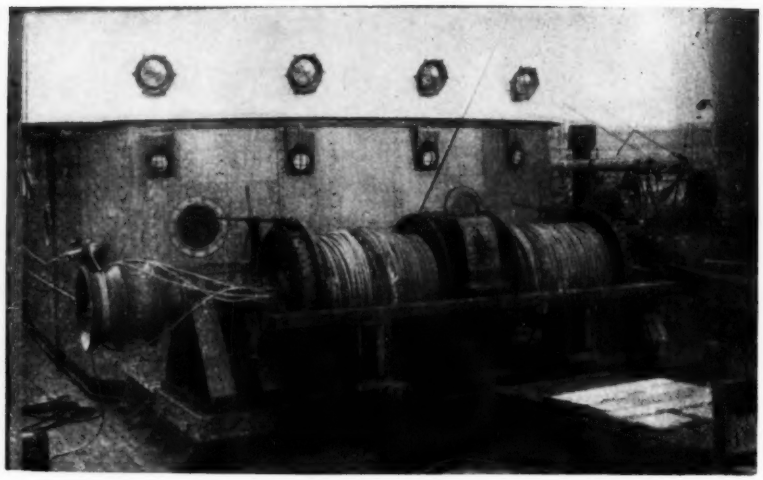


Fig. 7.—The trawl winch

Both these problems were solved by fitting the main engines with after-coolers and placing both the salt and fresh water systems under automatic thermostatic control. The salt water control keeps the discharge from the salt water circulating pump to the system at 65°F, regardless of the temperature at the sea water suction. Changes either in the temperature of this water or in plant loading only increase or decrease the amount of water discharged overboard from the system by varying the quantity of hot water returned to the automatically controlled 'Drayton' mixing valve situated at the pump suction. The discharge from the salt water circulating pump passes through the engine oil coolers to the air coolers and on to the heat exchanger ; because each engine system is balanced, no individual adjustment to engines is necessary. In the lowest ambient air temperatures the engine induction temperature, when idling, is not lower than 45°F and the oil temperatures remain within 2° of 140°F regardless of the power output.

A similar 'Drayton' mixing valve, on the suction side of the fresh water pump, keeps the engine cooling discharge temperature at 165° F ; changes in load vary the inlet temperature from 150°F at full power to 163°F when idling. The engineers make no adjustments throughout the voyage to this cooling system which has proved to be very effective. In the event of a failure of the automatically controlled valves a single hand-operated valve in each circuit provides emergency control. The automatic control of the jacket water temperatures has been used before but the system as applied to the salt water circulation, and its effect on the engine induction temperatures, is the subject of a recent patent application.

To control the quantity of air passing through the main generators in low ambient temperatures, and so maintain comfortable conditions in the engine room, a hand-operated damper is fitted at the air inlet to each of these machines. This is kept fully open at ambient temperatures of 50°F and above but as this temperature falls the air flow can be reduced to maintain the exhaust from the machines at about 50°F. High and low temperature alarms are fitted to give warning of incorrect damper adjustment.

Control System

Apart from the special features mentioned, which will be adopted in any future installations requiring any or all of them, the installation is similar to a number already in service and its general arrangement is as shown in Fig. 8. It will be seen that, despite dimensional limitations, the engine room is spacious and there is easy access to

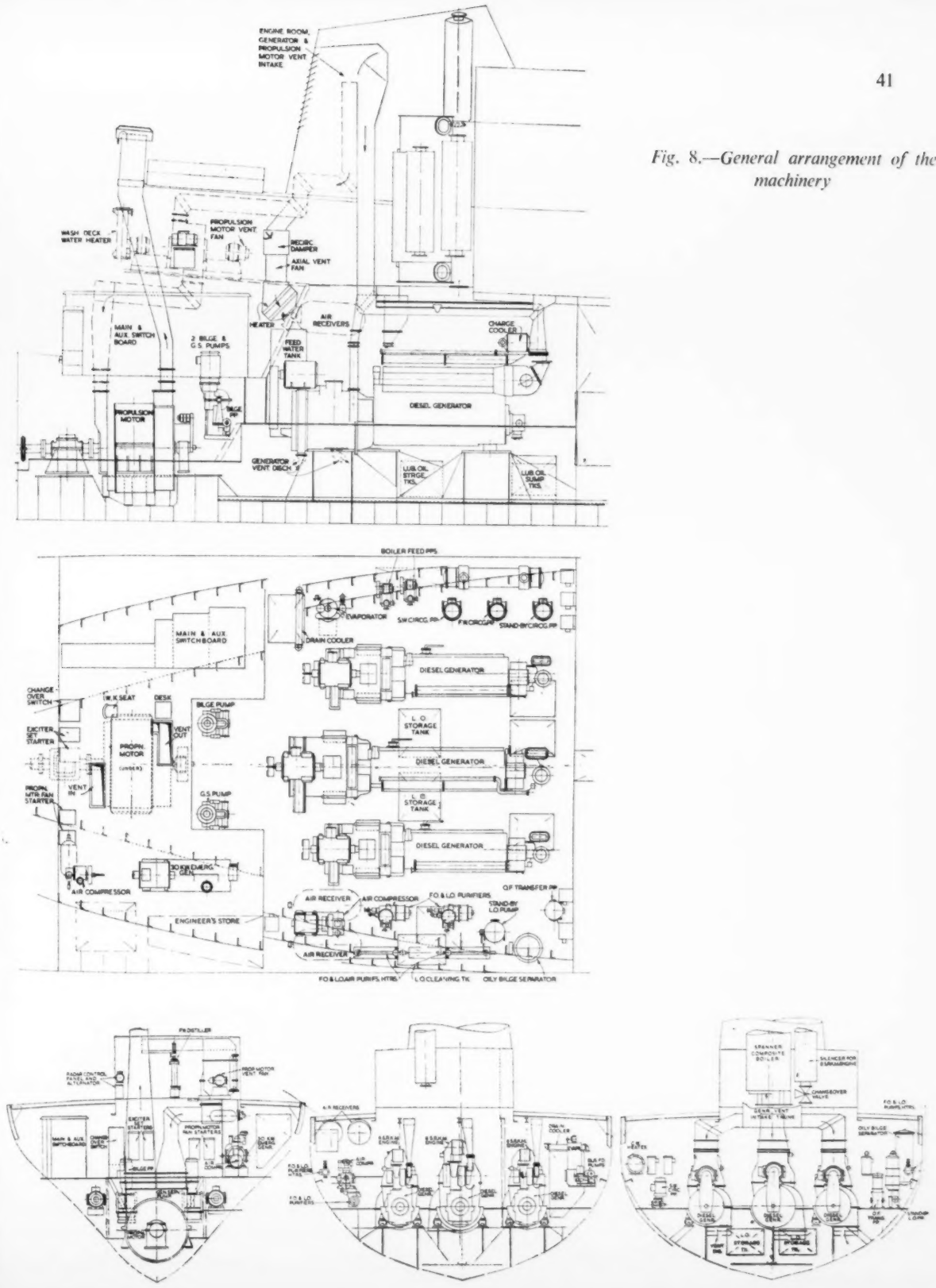


Fig. 8.—General arrangement of the machinery

machinery and control gear for maintenance and operation.

The three main generators and the propulsion motor are arranged in a series circuit and one, two or three generators can provide propulsion power, giving a high standard of reliability. Generators can be switched in or out of the propulsion circuit whilst the vessel is under way without interrupting propulsion power, and the engines cannot be overloaded in any condition of operation or 'set up', since the inherent characteristics of the system limit the power demand from the engines to their designed service rating.

The propulsion system is simple and inherently stable, and employs the minimum of working parts and extraneous protective devices. In this system the main generators are excited from a three-field exciter, the three field windings being :—

A self-excited shunt field connected through the propulsion controller resistors, and across the exciter terminals, and therefore responsive to the exciter voltage. The exciter voltage cannot build up on this field alone.

A separately-excited field energised from the auxiliary busbars through the propulsion controller resistors. This field controls the build-up of the exciter voltage.

A negative series field carrying the main circuit and opposing the self-excited and separately-excited fields.

The combined effect of these three fields is to give main generator characteristics as indicated in Fig. 9. The voltage is progressively reduced with increased current, and falls to zero at a predetermined point above the full load value. This results in a kW/current curve as shown with maximum power occurring at the normal working point. The main generators therefore have inherent non-overloading characteristics and, with the equipment correctly adjusted, the service rating of the diesel engines cannot be exceeded, regardless of the number of generators in circuit or the position of the propulsion motor controller. This characteristic also safeguards the machinery when the resistance on the propeller increases due to external conditions, but it does allow the production of higher than full load torques, up to a predetermined point of stall. The characteristics of the main generators are maintained at lower speed settings since movement of the propulsion controller reduces the separately- and self-excited field currents of the 3-field main generator exciter.

The separately-excited field and self-excited field of the main generator exciter, and therefore the voltage of the main generators, retain the same polarity with the propulsion controller in the

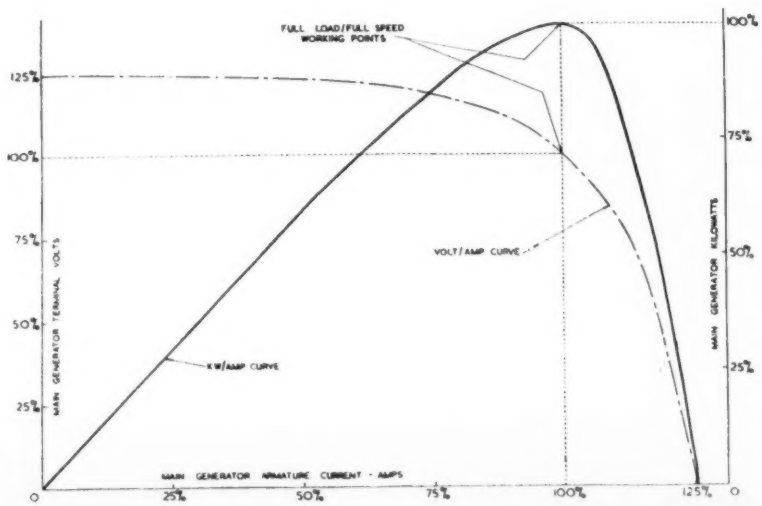


Fig. 9.—Main generator propulsion characteristics

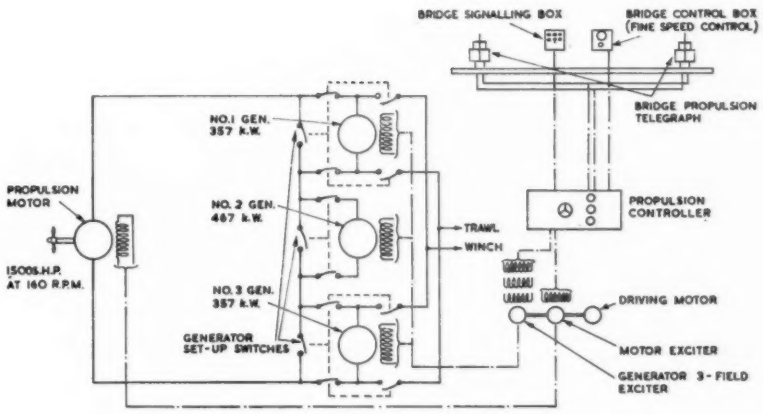


Fig. 10.—Simplified schematic diagram of electrical system

'Ahead' or 'Astern' position, the change of direction of propulsion motor rotation being obtained by reversal of motor field polarity. The propulsion motor is separately excited from its own exciter. This exciter has separately-excited fields, energised from the constant voltage auxiliary supply through a potentiometer in the motor controller. It also has a negative differential field in series with its armature and the propulsion motor field, to increase the rapidity of response to the controller movements. The propulsion motor controller acts on the self- and separately-excited fields of the generator exciter and on the field of the propulsion motor exciter. The scheme in this installation is as shown in Fig. 10.

The propulsion motor can be controlled either directly from the bridge or from the engine room in response to telegraphed orders. For normal manoeuvring the fixed speed steps of the bridge telegraph/controllers give adequate propeller speed control, but when fishing a finer adjustment is required. This is provided by a Vernier control on the bridge propeller-speed indicator, by which any speed between the speed steps on the telegraph can be selected. Since this adjustment cannot exceed the chosen speed step on the telegraph it cannot be mal-operated.

A separate source of power to the trawl winch is not necessary in the 'Portia'. Either the port or

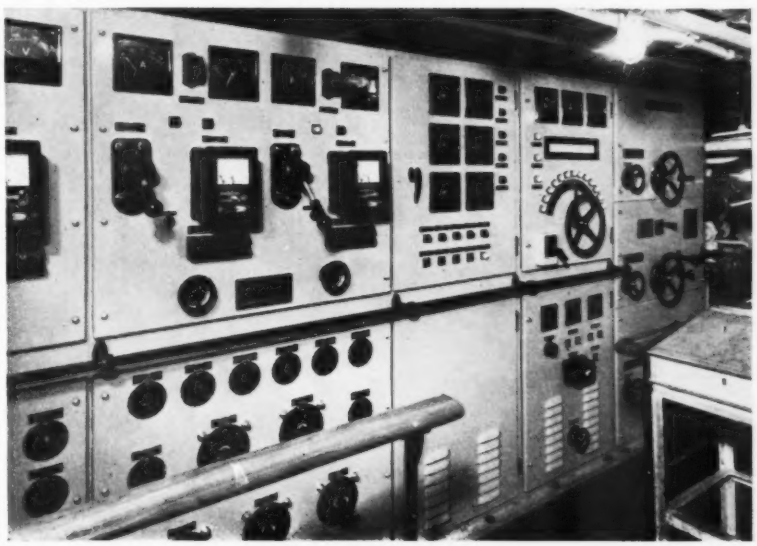


Fig. 11.—The main and auxiliary control board

starboard main generator can be switched from the propulsion to the trawl winch circuit through its respective ' set up ' switch which, as already mentioned, has three positions, ' Propulsion ', ' Off ' and ' Trawl '; mechanical interlocks prevent more than one generator being switched into the winch circuit at any time.

To facilitate operation of the machinery the main control board (Fig. 11) is comprehensively instrumented. A kilowatt meter and a voltmeter are provided for each main generator ; a circuit current ammeter, shaft horse-power meter and propeller speed indicator register the performance of the propulsion motor. Indicating, signalling and electrical circuit alarm equipments are included in the main control board which is fitted with removable panels permitting ease of access to all components. A hand-operated torque controlling rheostat is fitted to allow the propulsion motor torque to be increased to compensate for the fall in propeller revolutions when towing the trawl ; this ensures that full advantage can be taken of the engine power available when one or two generating sets are supplying propulsion power.

Propulsion Motor

The single-armature 850 volts d.c. propulsion motor (Fig. 12) delivers 1,500 s.h.p. at 160 r.p.m. It is a totally-enclosed forced-ventilated machine with class ' B ' insulation, designed for unrestricted operation in any climate, and it is watertight to two feet above the shaft line. It is supplied with ventilating air from deck level by a ' Howden ' centrifugal fan which has two driving motors, one working and one standby.

Main Engines

Three ' English Electric ' Type CSRKM, four-stroke, exhaust turbo-charged and after-cooled diesel engines supply power to the main and auxiliary generators. This type of engine is designed to run at 750 r.p.m., with a b.m.e.p. of 140 lb/sq in at the 12-hour British Standard rating. In this installation they have been derated to 700 r.p.m. and 114 lb/sq in b.m.e.p. for continuous unrestricted operation. Each engine is direct coupled to a flange-mounted main generator, and a 60 kW 220 volts d.c. constant-voltage auxiliary generator is mounted on top of the main generator and is chain driven from it. Following the normal ' English Electric ' practice for installations of this type the combined engine and generator unit is mounted on a ' three point ' support. This system gives clear access around the set, obviates the need for a combination baseplate and protects the generating set against mal-alignment arising from the ' working ' of the vessel's hull.

The centre generating set is powered by an

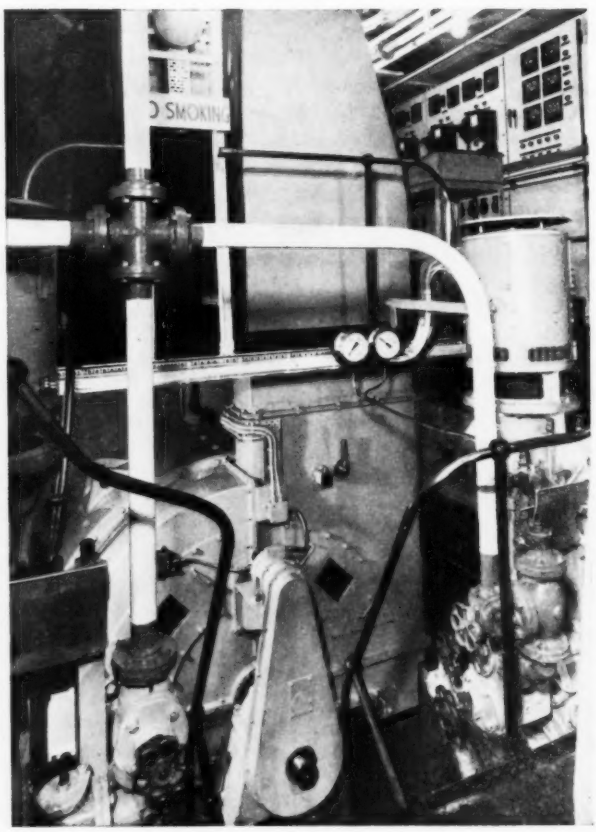


Fig. 12.—*The propulsion motor*

eight-cylinder engine and its main generator delivers 467 kW at 340 volts. The two wing generating sets (Fig. 13) have six-cylinder engines and deliver 357 kW when on propulsion duties or 240 kW on the winch, at 255 volts. Like the propulsion motor the main generators are enclosed machines with class 'B' insulation and are designed for unrestricted operation in any climate. They are self ventilated by integral fans mounted on their armature shafts, which draw ventilating air through trunking from deck level and exhaust it into the engine room below the floor plates.

Engine lubrication is on the semi-dry sump principle. A gear type pressure pump, driven from the engine crankshaft, draws oil from the sump tank and delivers it through magnetic and duplex filters and an oil cooler to the main supply rail ; the oil returns to the sump tank by gravity. Centrifuges purify the oil in each of the sump tanks in rotation. Low oil pressure alarms are fitted to each engine, and a motor-driven lubricating oil pump is provided for standby service to any of the three engines.

As is standard practice for engines of this type, they are fresh water cooled. The fresh water circuit is supplied by an independent motor-driven pump and the water from all engines is cooled in a single 'Serck' heat exchanger ; this allows an idle engine to be kept warm and ready for immediate service. A motor-driven salt water circulating pump supplies all three engine oil and air cooling systems in parallel. An independent motor-driven salt/fresh water pump acts as standby to either working pump. Low pressure and high and low temperature alarms are fitted in both water systems. The special arrangements of these two systems to ensure reliable working in the arduous conditions encountered have been mentioned previously.

Auxiliary Services

Dry saturated steam at 80 lb/sq in for liver boiling plant, de-icing, accommodation heating and domestic use is supplied by a 'Spanner' composite boiler mounted on a flat above the engines at main deck level. Because of the varying load factor of the wing engines when on winch duty, the centre engine exhaust only can be diverted through this boiler. On exhaust gas only from the engine at full service power, the boiler delivers 700 lb of steam per hour. When the demand exceeds this quantity the oil fired section of the boiler automatically comes in to augment the supply, and this section can generate up to 1,800 lb of steam per hour.

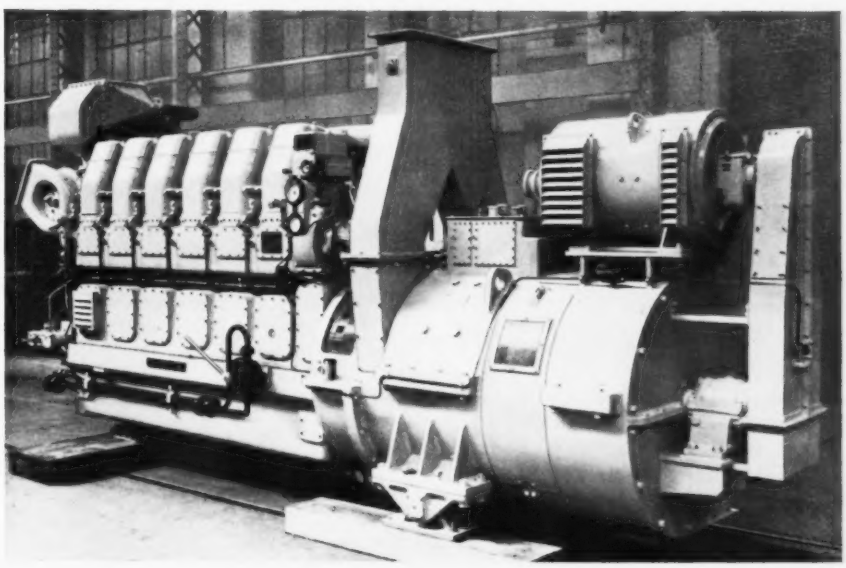


Fig. 13.—One of the two 357 kW wing diesel-generating sets

A 30 kW diesel-generating set provides power when the ship is in port, and the two 23 cu ft capacity air receivers are charged by a 16 cu ft motor-driven air compressor. For emergency use, or first starting with all services ' dead ', a 5 cu ft hand-starting diesel-driven air compressor is provided. Two motor-driven reciprocating bilge and general service pumps are installed and the domestic salt and fresh water services operate on pressure systems supplied by positive displacement type motor-driven pumps. To prevent pollution of water in the docks the bilge pumps discharge through an oily bilge water separator. A small evaporating plant, with distiller, ensures that the ship can maintain its fresh water requirements on the longest voyages contemplated.

Operating Experience

It has already been mentioned that the winter months of 1956-57 have proved that ' Portia ' is a very successful design of ship for this service. It is yet too soon to analyse the machinery performance since some time must elapse before the pattern of maintenance costs can be established. However, it is clear that diesel-electric machinery does meet all service requirements and, as installed in ' Portia', will stand up to the severe conditions prevailing in distant-water trawlers. The three engineers handle the machinery with confidence and skill, and a regular maintenance routine has been established which promises to keep the plant in first-class order, within the limits of the normal stay in port for this class of ship.

It has been found that on a normal fishing trip ' Portia ' burns an average of 4·9 tons of marine diesel fuel and uses 10 gallons of lubricating oil a day, this when developing 1,500 s.h.p. (1,750 i.h.p.) on the voyage to and from the fishing grounds. The annual bill is therefore approximately £19,200, again based on prices prevailing before the Suez Canal crisis, against the £24,600 for a comparable steam driven vessel of 1,200 i.h.p. It is anticipated that this saving, when equated against maintenance and the amortisation of the more expensive type of machinery, will leave a financial gain to be added to the performance assets of this outstanding new vessel.

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